SEASAT-A SCIENTIFIC CONTRIBUTIONS

July 1974

(NASA-TM-X-72944) SEASAT-A SCIENTIFIC CONTRIBUTIONS (NASA) 172 p HC $6.75 CSCL 05B
N76-11482 THRU N76-11508
Unclas
G3/42 03104

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

FOREWORD

This report has been prepared in order to provide an estimate of the scientific contributions expected from SEASAT-A. At the time of writing, the instrument complement and capabilities planned were those set forth in the first and last sections of this discussion. As the report went to press, the decision was reached on the basis of resource considerations to employ a SEASAT-A instrument complement which would not include the microwave radiometer. This decision was taken in the light of the agency's plan to fly a similar instrument on Nimbus-G, which is scheduled to be launched at about the same time as SEASAT-A. Data from the Nimbus-G version of the radiometer will have a somewhat coarser spatial resolution, will be taken at times differing from those of the SEASAT-A observations by as much as a quarter of a day and, according to plans at this point, will not include measures from the low-frequency channel which is sensitive to ocean temperature. Effects of such a change can be estimated on the basis of material in the report including, for example, the tables in the first and last sections and related passages. Efforts to work out a way to include the microwave radiometer in the SEASAT-A instrument complement are continuing.

CONTENTS

PRECEDING PAGE BLANK NOT FILMED

I. A SYNOPSIS OF SEASAT-A SCIENTIFIC CONTRIBUTIONS

A SYNOPSIS OF SEASAT-A SCIENTIFIC CONTRIBUTIONS

John R. Apel
National Oceanic and Atmospheric Administration
and
Joseph W. Siry
National Aeronautics and Space Administration

INTRODUCTION

The SEASAT-A Mission is a key element of the NASA Earth and Ocean Physics Applications Program (EOPAP) (*NASA*, 1972). It is expected to make major contributions to ocean science and lead to a number of significant advances in the study of the atmosphere and the solid earth as well. It will complement existing and planned research and observational activities.

The SEASAT-A program is aimed largely at conducting the research upon which future applications will be based. It involves not only the spacecraft but also accurate ground tracking systems and data processing and modeling capabilities that will address scientific and applications problems in the domains of oceanic, atmospheric, and solid earth geophysics. It brings together for the first time a unified set of active radar and passive microwave and infrared instruments that give it the capability of making observations both day and night under nearly all types of weather conditions. Its orbit will span all of the unfrozen and some of the ice-covered oceans of the world in an 800 km altitude, non-sun-synchronous path (Figure 1). It is thus an integrated geophysical observatory which will yield a wide variety of data of interest to scientists in a number of different disciplines. Its impact on ocean science will come about through the provision of synoptic and global scale observations of a set of important quantities describing the dynamics of the upper ocean. Such parameters as surface wave spectra, surface wind velocities, sea surface temperatures (including those in regions lying under clouds), and leads and openings through the ice fields should be measurable with useful accuracies. In addition, SEASAT-A will permit systematic steps leading toward the measurement of deep sea tides and the major surface currents and circulations, including their variations in space and time. Meteorology and climatology, viewed as planetary sciences, should also benefit from the SEASAT-A Mission through its provision of the first global-scale data on surface wind fields. Measurements of the temperature of the portions of the ocean surface lying under persistent cloud cover will fill significant gaps in our observational knowledge of factors affecting the atmosphere on time scales ranging from days to months and longer. Solid earth sciences will also benefit in several ways from the SEASAT-A results. The detailed knowledge of both the ocean geoid and the combined solid earth and ocean tides gleaned from the data will shed new light on the gravity field and the structure and dynamics of the earth's crust.

A detailed description of the SEASAT-A Mission appears in a review of the EOPAP Ocean Dynamics Program contained in Section III (*Apel and Siry*, this report, 1974). That discussion also includes a summary of the characteristics of GEOS-C, a spacecraft with a more limited oceanographic capability which is scheduled for launching around the end of this year, and a report of some of the Skylab results which are of interest from the standpoint of ocean science. The geophysical parameters to be determined from SEASAT-A and the range and accuracy of the measurements are discussed in Section III.

While SEASAT-A is a NASA applications program, a number of other institutions have

been actively involved with NASA in planning the project, and will continue their contribution as data users. Among them are many departments and agencies of the Federal government, universities, and other organizations in the private sector which are concerned with maritime affairs (cf. Section III). The guidance lent by these organizations in establishing the scientific and applications objectives, designing the mission, and specifying the data form and flow have helped to assure the utility of the program to a large community of marine interests, including scientific interests.

The views of a number of scientists have been sought in order to obtain an estimate of the value of the SEASAT-A Mission from the scientific standpoint. Their views concerning its science potential and, to an extent, its applications benefits are contained in Section II. The individual contributions there deal with a number of specific, related scientific topics in oceanography, meteorology, and solid earth physics. A summary of these contributions is contained in the following discussion.

Much of the material deals with accomplishments for which the probability of success is reasonably high. The NASA Earth and Ocean Physics Applications Program (EOPAP) plan includes the conducting, in the SEASAT-A program, of certain key exploratory experiments such as those requiring accurate determination of sea surface topography and spacecraft orbits (*NASA*, 1972). It is anticipated that the results of these experiments will be valuable in their own right and will pave the way for fuller realization in later phases of EOPAP of the goals involving accurate sea surface topography.

OCEANOGRAPHY, METEOROLOGY, AND CLIMATOLOGY

Waves

SEASAT-A should reveal the principal features of the dynamic behavior of ocean gravity waves, about which we now have a dearth of quantitative data. Many fundamental questions remain largely unanswered. A comparison between theory and observation has been difficult to obtain in large part due to the absence of adequate experimental data on waves, especially under storm conditions. Because of this lack, not enough is known about the genesis of waves in response to winds, their changing characteristics as they propagate over the ocean surface, their interactions with other surface wave fields, their generating, in turn, of internal waves, their trapping and refraction by strong currents, and their attenuation as they enter shallow waters and suffer major changes in amplitude, speed, and direction before finally dissipating their remaining energy in erosive, often destructive assaults on the coasts. The most basic description, the complete wave directional spectrum, $S(\mathbf{k},\omega)$, as a function of the wave vector $\mathbf{k}$ and the frequency ω has never been measured at all (*Stewart*, this report, 1974).

Wave Heights—The wave height information presently available is generated largely by ships at sea. The bulk of the information comes from some twelve hundred ships, mostly in the Northern Hemisphere, which report wave conditions in terms of height, period, and dominant direction of travel. It is to be emphasized that these are not measurements, but are estimates which have been found, when actually compared with a few real measures, to be in error, frequently by a factor of two (*Pierson*, this report, 1974a).

SEASAT-A will make measurements of significant wave height, $H_{1/3}$, by means of its short pulse altimeter, the return pulse broadening being a function of the wave amplitude. These measures will be good to 0.5 meter or ± 10% in the 1-20 meter range and will be uniformly distributed over all the world's unfrozen oceans at a measurement density sufficiently great to permit the obtaining of good information about signifi-

cant spatial variations along the orbital track (Cf. section III of this report). Accurate measurements of wave height every 50 kilometers, for example, which is a reasonable operational schedule for SEASAT-A, will result in some 7000 observations per day.

Wave Directional Spectra—A very few weather ships, 4 or 5 in the North Atlantic and a single one in the North Pacific, record the wave height as a function of time at a point. Non-directional frequency spectra, $S(\omega)$, can be deduced from such records (*Pierson*, this report, 1974a; *Stewart*, this report, 1974).

SEASAT-A will record wave directional spectra (i.e., wave amplitude as a function of wavelength and propagation direction) at some 500 or 600 locations in both hemispheres, using the coherent imaging radar of the type discussed in the last section. It will thus, for the first time, furnish global, synoptic measures of wave height and directional spectra which, together with the wind field, constitute the most basic quantities needed for open-ocean wave forecasting.

Wave Images—Where a wave field is not statistically homogeneous, a spectral description is not adequate and wave images are required instead. This is true, for example, of waves generated by intense storms, or in the study of refraction of waves as they enter shallower water, where bathymetric features can lead to large concentrations or dilutions of wave energy (cf. *Teleki*, this report, 1974). Here, images of the type seen in Figure 2(a) will be most valuable, especially under storm conditions when ordinary photography fails (*Baer*, this report, 1974). This picture was obtained by means of a synthetic aperture, imaging radar operating in an aircraft off Kayak Island, Alaska (seen on the left). Also shown are examples of wave directional spectra (Figures 2(b) and (c)). The coherent imaging radar planned for SEASAT-A will provide images and spectra of this type (cf. Section III).

Wave generation, propagation, interaction, and absorption can be studied experimentally for a variety of conditions of wind speed, fetch, and duration, using such data. Wave trapping and refraction through encounters with current systems is another phenomenon which can be elucidated by means of SEASAT-A wave images. Coupling between surface waves and internal waves can also be studied with the aid of imagery (cf. *Stewart*, this report, 1974). Evidence has already been presented that effects of internal waves are discernible in ERTS images in the visible and near-infrared regions of the spectrum (*Apel, Proni, and Charnell*, 1974).

Sea Surface Temperature

The temperature of the ocean's surface, another one of its basic characteristics, is currently mapped over cloud-free portions of the ocean by infrared radiometers operating on Nimbus, NOAA and SMS satellites, with precisions approaching ±1°C. The temperatures of the remaining beclouded portions of the ocean surface are presently determined only from ships or buoys, however. SEASAT-A's multichannel microwave radiometer will map sea surface temperature under conditions of clouds or light rains, albeit with considerably coarser spatial resolution and somewhat lower temperature precision than the infrared instruments (cf. Section III). However, the microwave measurements should represent bulk ocean temperatures more closely than the infrared measures do, particularly under conditions where light surface winds result in little surface mixing (*Sherman and Rao*, this report, 1974). The microwave radiometer, in order to correct the sea temperature measurement for effects of atmospheric liquid and vaporous water and surface foam and roughness, must make independent determinations of these quantities by using several frequencies and two polarizations. The records of the several channels, taken together, form the basis for the determination of sea

surface temperature, foam and roughness and hence high wind speeds, cloud distribution, atmospheric water vapor content, and sea and lake ice cover. The imagery of Figure 3, for example, was obtained from the Nimbus 5 microwave scanning radiometer, and shows ice, rainfall, and the near-permanent cloud cover over the Intertropical Convergence Zone.

Sea temperature is a parameter of considerable importance in oceanic and atmospheric processes, since it reflects the absorption by the sea of that prime mover, solar energy. The difference between active and inactive hurricane seasons may be due to water temperatures in hurricane gestation areas just 2 to 3°C lower than average. Ocean temperature is a major factor in determining the tone of weather and climate in coastal regions of the world and indeed, as the North Pacific Experiment suggests, may control short term climate on a continental scale through its influence on the circumpolar jet stream. Maps of sea surface temperatures are very useful for understanding the dynamics of current systems such as the Gulf Stream or Kuroshio, especially in winter and spring. Furthermore, open-ocean fish such as tuna tend to swim along lines of constant temperature at certain times in their excursions and thus ocean temperatures assist in marine biological studies. In persistently cloudy areas such as the Intertropical Convergence Zone or the Antarctic Circumpolar Current region, temperatures derived from a microwave radiometer will be of special value. Knowledge of sea surface temperature will also be important in connection with studies of marine fog (*Ruskin and Jeck,* this report, 1974).

Ice Fields and Leads

Ice will be studied in several ways during the SEASAT-A Mission. The small-scale features of lake and polar ice fields will be sampled frequently by the coherent imaging radar, thereby providing data needed to chart ice leads, surface roughness characteristics, and motions of ridges, polynas, and openings in the ice. This information will be of value in studying the structure and dynamics of ice formations (*Campbell,* this report, 1974; *Noble,* this report, 1974). Furthermore, there are indications that the age and thickness of ice may be determined from a properly configured imaging radar.

On a coarser but more nearly global scale, the microwave scanning radiometer should provide images of ice cover that can be used to extrapolate the fine-grained imaging radar coverage. Delineations of the edges of ice packs and glaciers and the general advance and retreat of ice cover should be possible with this device.

The information about the ice leads and openings will also be of value in connection with the all-weather determination of heat transfer into the atmosphere, which proceeds approximately 1000 times more rapidly across the water than the ice interface. Such data will be valuable for weather and climate studies in the polar regions, where much of the world's weather is spawned (*Weeks,* this report, 1974).

Sea Surface Topography

The marine geoid is defined as the surface which would be assumed by a motionless, uniform ocean under the influence of the earth's gravity and rotation, and uniform atmospheric pressure. Thus, it reflects only the effects of gravitational and gross centripetal forces. Departures of the sea surface from the geoid due to tides, currents, coriolis force, wind, pressure, and wave-making and other forces are grouped under the term "sea surface topography." These departures, if measurable, can often be used to derive information on the forcing functions themselves.

The general strategy planned for conducting these topographical experiments with SEASAT-A includes the focusing of efforts in the Western North Atlantic Quadrangle region defined by Goddard, Bermuda, Grand

Turk, and Cape Kennedy where laser trackers will yield accurate orbital heights for SEASAT-A, and relatively good geoid information is available. The aim is to determine the sea surface topography to about a third of a meter in this area, and to one or two meters elsewhere, or about half an order of magnitude better than in the case of GEOS-C. In addition, the coverage patterns will be more uniform and complete in the case of SEASAT-A.

The Gulf stream traverses this quadrangle and, in fact, exhibits all its major features in the area, i.e., relatively steady flow, meanders, and eddies (cf. Figure 4; *Hansen,* 1970; *Siry,* 1973b).

Tides—The M_2 tidal signal is relatively strong in the quadrangle, and the orbital paths are nearly parallel and orthogonal to the co-range lines there (cf., e.g., Figure 5; *Hansen*, 1949; *Siry*, 1973b). The complicated, ill-understood transition from deep sea to coastal tides can also be studied here.

The deep ocean tides have amplitudes of the order of a meter (cf. Figure 6; *Hendershott and Munk*, 1970). It is anticipated that the determination of the deep ocean tides on a global basis may be attempted by analyzing the entire ensemble of data gathered over a period of a year and solving, say, for tidal amplitudes and phases, dissipation parameters, and quantities representing the yielding of the solid earth in response to both the lunisolar gravitational effects and the loading of the ocean tides themselves (cf. *Hendershott, Munk, and Zetler*, this report, 1974). Tidal dissipations are thought to occur mainly in regions of broad continental shelves, such as the Patagonian Shelf and the Bering Sea.

Currents and the Oceanic Pressure Gradient—The movement of water on a rotating earth leads to a departure of the surface of the ocean from the geoidal equipotential surface due to the balance between the horizontal component of the coriolis acceleration and the resultant horizontal pressure gradient. The steady components of the dynamic topography of the sea surface have an extreme range of the order of 2 meters, as shown in Figure 7 *(Stommel,* 1964). The topographic relief is particularly pronounced in the vicinity of western boundary currents and large oceanic eddies, or rings. The dynamic topography for the western Atlantic, as calculated from essentially climatological density data, is shown in Figure 8. The mean position of the Gulf Stream is clearly defined via its meter relief. The actual Gulf Stream is a much more dynamic feature, exhibiting meanders having one-to-six-week periods and wavelengths approaching 300 km (cf. Figure 4, *Hansen,* 1970). It sheds rings or eddies of comparable size at a rate of several per year, which maintain their current and associated topographic signatures for many months.

The SEASAT-A instrument complement will also include a thermal infrared imager which will aid in identifying and locating ocean features such as currents, and thus facilitate the interpretation of the altimeter records (*Robe,* this report, 1974). An image of this type obtained from the NOAA-2 satellite is seen in Figure 9 (cf. also the last section of this report).

The combination of precision altimetry, orbit analysis, and geoidal modeling will allow measurements of the slope of the local surface of the ocean relative to the geoid. This slope can be related to the absolute horizontal pressure gradient and hence the surface current velocity through the use of the fluid dynamical equations in the geostrophic approximation (*Bryan*, this report, 1974; *Byrne and VonArx*, this report, 1974). The precision of this velocity determination will depend on the precisions of the three measurements entering into the slope calculation, but for SEASAT-A, it should amount to some two-thirds of a meter per second in the quadrangle area. Better results will be looked for as experience is gained in interpreting time varying signatures. This approach, when

combined with the sampling density shown in Figure 4, should allow both Gulf Stream and eddy dynamics to be studied on a scale approached by no other means.

It is anticipated that the lessons learned in the quadrangle region will facilitate attempts to detect ocean topography effects out into the Atlantic and elsewhere. During three days, the SEASAT-A precision altimeter and tracking systems will yield measurements along subsatellite tracks with an equatorial spacing of approximately 500 km (and even less at higher latitudes). In three months, the tracks should overlay the equator at about 15 km intervals. Variable topographic features which have sufficiently long time constants (or are periodic) and are large enough to be sampled with this measurement precision and density should be discernible against spatial variations in the background geoid.

It is anticipated, for example, that this approach will be used to search for the transient mid-ocean currents, of a spatial scale of the order of 5°, which have recently been seen. Following them over the oceans as a whole will help greatly in the effort to understand how they interact with the mean general circulation of the ocean, and thereby contribute significantly to the solution of the central problem in physical oceanography at the present time (*Bryan*, this report, 1974).

Tsunamis, Set-Up, and Storm Surges—Other oceanic departures from the geoid should be observable in the altimetric signal if the satellite is overhead at the time and place of occurrence. For example, a seismically excited wave, or tsunami, should be detectable in mid-ocean as a near-periodic topographic ripple of perhaps 50 cm range and a couple of hundred kilometers in wavelength. Since these disturbances last for tens of hours and ultimately traverse the entire ocean basin, there is a reasonable probability of observing one if it should occur during the lifetime of the spacecraft. The amplitude of a deep-ocean tsunami has never been measured.

Similarly, variations in the set-up of water against the coast due to longer term wind stress will be looked for, and the extreme form of this phenomenon, the storm surge, should be observable if the timing and positioning relative to the satellite track are correct. Such an observation of a storm surge is a low-probability event but, if obtained, the data would be extremely valuable as checks on storm surge prediction models.

SEASAT-A will probably not solve the problems of ocean tides, currents and circulations completely, however, its accurate altimetry will permit important exploratory experiments to be conducted in all these areas. They should yield data which will be of much intrinsic value, and will provide the foundation for planning the next phase of the program in these areas of ocean science (*NASA*, 1972; *Siry*, 1973a).

Meteorology and Climatology

Surface Winds—SEASAT-A will measure surface wind speeds, and to some extent, directions, by means of a scatterometer and a microwave radiometer. The former relies on Bragg scattering from wind-generated capillary waves, while the latter senses the increase in brightness temperature due to foam and roughness. The fraction of the surface covered by the capillaries or the foam and roughness is a function of wind speed (cf. the last section of this report). These instruments have both been operated on aircraft missions and on Skylab. Radar scatter, emission, and wind speed results obtained during a Skylab passage near the Pacific hurricane Ava are indicated in Figure 10.

The SEASAT-A surface wind data will be equivalent to some 20,000 ship reports each day, roughly an order of magnitude larger than that presently provided by surface vessels. Again, they will be more or less uniformly distributed over the global oceans, thus filling the major gaps in the meteorological coverage patterns which result from

the fact that ships are concentrated in the Northern Hemisphere, largely in the shipping lanes (cf. *Pierson*, this report, 1974b; *Shemdin*, this report, 1974). Using wind data from the spacecraft in conjunction with ship, buoy, and island information, it appears possible to define the vector surface wind field throughout the planetary boundary layer every 24 hours, for speeds from 4 to 5 m/sec to perhaps whole gale force or greater, on a relatively uniform grid of approximately 1400 km spacing.

The definition of the surface wind over the oceans will be a large step forward in ocean wave forecasting (*Noble*, this report, 1974; Ruskin and Jeck, this report, 1974). The wind data, used in conjunction with other surface-derived information and wave directional spectra supplied by SEASAT-A as both initial and boundary values of the surface wave field, will allow development of an advanced, computerized global wave forecast model (*Pierson* , this report, 1974b) whose potential monetary value to marine interests is immense (cf. *NASA*, "Economic Benefits of the SEASAT System," 1974). Scientific problems in wind-wave interactions, such as the generation and radiation of waves by intense storms, and in mixing processes in the upper layers of the ocean, may be studied using the enhanced base of global data on winds, waves, and ocean temperatures.

The Planetary Atmosphere—Coming, as they will, at the time of the Global Atmosphere Research Project (GARP)/First GARP Global Experiment (FGGE) activities, these SEASAT-A results will be especially relevant to the science of the atmosphere. The measurements of winds in the tropics and of sea surface temperatures to be made by SEASAT-A are expected to be of real value in connection with weather studies in general and the FGGE in particular. SEASAT-A is also likely to play a useful role in the longer range studies aimed at the second objective of GARP which is to investigate "the factors that determine the statistical properties of the general circulation of the atmosphere which would lead to a better understanding of the physical basis of climate" (*GARP*, 1973; *Kellogg*, this report, 1974).

A significant improvement in the quality of the planetary weather forecasts in the one-to-three-day interval is expected to result from the infusion of SEASAT-A data into global weather prediction models. The improvements will occur not only over the oceans but also over continental areas, such as the east coast and the western half of the United States, which are strongly affected by maritime conditions. The data-sparse Southern Hemisphere will benefit especially. The quality of the forecasts there will increase substantially. This will result in both scientific and general gains in terms of our understanding of the atmosphere and the weather, and will permit studies of inter-hemisphere interactions to get underway in earnest. The fierce meteorological systems surrounding the Antarctic continent will also be susceptible to orderly study on a synoptic scale for the first time.

It is obvious that SEASAT-A data will only form a portion of the total meteorological information entering into synoptic or global scale weather and climate studies. However, this expanded data base, containing global measurements of surface wind, waves, and sea temperature, will be an important and often unique adjunct to the data obtained from surface sources and from other spacecraft.

SOLID EARTH PHYSICS

The Ocean Geoid

Although SEASAT-A is designed primarily to give oceanic and atmospheric information, it will contribute significantly to solid earth geophysics as well.

The present knowledge of the geoid is based on observations of gravitational perturbations of satellite orbits, which reflect global features (cf. Figure 11), and surface

gravimetry which provides details in some local areas such as the one indicated in Figure 12 (cf. *Smith*, this report, 1974). The spatial resolution of the latter is considerably better than in the case of the global geoid, as can be seen from comparison with Figure 11. In that figure, the characteristic spatial scale of the discernible gravity features is of the same order as the altitudes of most of the satellites which sensed them, i.e., about ten to fifteen degrees. The satellite altimeter approach offers the best prospect for acquiring high-resolution ocean geoid data on a global basis. It has very large advantages over the conventional surface ship method in terms of the practicalities of achieving worldwide coverage (*Mourad*, this report, 1974). The geoid data provided by the altimeter are not attenuated by height. The regular coverage patterns of SEASAT-A will improve the spatial resolution of the global geoid. The height resolution is expected to be improved to a scale of the order of a meter (cf., e.g., *Chovitz*, this report, 1974).

The combination of satellite altimetry with surface gravimetry is also expected to yield important results concerning geoid perturbations (*Bowin*, this report, 1974). An example of the capability actually achieved with the altimeter operating on Skylab is seen in Figure 13 (*Hoge*, this report, 1974). This instrument has already discovered new geoidal features (*Bowin*, this report, 1974).

The fine structure of the geoid to be traced out by the SEASAT-A altimeter system can thus be expected to reveal a great deal of information about the structure and dynamics of the earth's crust. The small-scale undulations of the ocean geoid are manifestations of gravity anomalies which reflect density irregularities of corresponding scale and/or depth. Many of these, in turn, are considered to result from temperature patterns associated with convective flows within the asthenosphere. Upcurrents due to convection are thought to occur at ocean rise crests, and on their volcanic flanks.

Lithospheric dynamics will also be partially elucidated by the high resolution surface gravity mapping obtained from SEASAT-A. The understanding of tectonic plate behavior near subduction zones associated with such phenomena as compressive upbuckling will be increased.

A continuing interplay between the oceans and the solid earth is seen again in the continental shelves and abyssal plains, which are heavily sedimented. The sedimentation process is influenced in significant ways by ocean waves, currents, temperatures, and nutrient levels. Thus, this aspect of the solid earth's structure can be better understood through an increased knowledge of ocean dynamics (*Kaula*, this report, 1974).

Fine resolution gravity maps will also permit more effective planning of other types of geophysical surveys that use, for example, heat flow probes, dredge hauls, seismic refraction profilometers, drill cores, and precision depth sounders.

Solid Earth Tidal Studies

The ocean tidal studies will also yield data on the solid earth tides. As mentioned earlier, the problem of the ocean tides actually cannot be fully solved without simultaneously determining the elastic behavior of the solid earth as it responds not only to the lunisolar gravitational attractions but also to the loading due to the ocean tides themselves.

Once the ocean tides are known, intriguing possibilities for detailed probing of the solid earth can be opened up. For example, the ocean tidal currents flowing in the earth's magnetic field generate electric potentials which are functions of the conductivity of both sea water and the solid earth. Once the tides and currents are known, the influence of the solid earth on the potentials may be estimated, and the corresponding effective conductivity as a function of effective depth in the earth can be deduced. Through this route, one may derive information about the temperature distribution within the earth's

upper mantle, and draw inferences about the stress fields that may be responsible for seismic activity (*Hendershott, Munk, and Zetler*, this report, 1974).

Oceanographic and Geodetic Leveling

Oceanographic and geodetic methods have both been used to determine the positions of the level surfaces along both the east and west coasts of the United States. Mean sea level appears to slope upward from south to north by nearly a meter, relative to land based spirit leveling (*Sturges*, this report, 1974). This discrepancy cannot be explained in terms of the estimated accuracies of the two procedures. The SEASAT-A Mission, with its capability for accurate determination of sea surface topography along the U.S. East Coast, for example, may offer prospects for helping to resolve this long-standing controversy (*Chovitz*, this report, 1974).

ORBITAL DYNAMICS

The very accurate tracking and altimetric systems employed in the SEASAT-A program will lead to considerable refinements in the science of orbital dynamics. The effects of high-order gravity perturbations will be better understood and accounted for (*Chovitz*, this report, 1974). Non-gravitational perturbations such as those due to solar radiation pressure and residual atmospheric drag will be determined with increased accuracy. One result will be improved orbit determination and prediction models for other earth-orbiting satellites (cf., e.g., *Smith*, this report, 1974).

ENGINEERING SCIENCE

A high-technology system such as a spacecraft and the associated ground facilities always brings along with it a number of important developments in engineering science and technology. While it is difficult to specify exactly what will be the yield of SEASAT-A in this regard, it is safe to speculate that in the areas of microwave sensors, in laser and radar tracking technology, and perhaps in data handling and dissemination, significant advances are to be expected. It is likely that other areas in space technology will be upgraded during the program, as well.

SUMMARY

Figure 14 shows the data flow required, the interrelationships between SEASAT-A instruments and other sources of information, and the geophysical parameters to be determined. As can be seen, each parameter requires data from several sources in order to achieve that measurement objective. Many parameters must, accordingly, be determined simultaneously. This leads to a richness of the total data set to flow from the system. The projected capability of the SEASAT-A Mission in meeting measurement objectives is summarized on Table I, which lists the chief physical parameters to be determined from it, along with estimates of range, precision, and spatial resolution.

The variety and number of scientific disciplines which are expected to benefit from the different types of observations are indicated in Table II. SEASAT-A promises to be an exceptionally useful and productive program. It should have a large impact on an unusually broad spectrum of disciplines of the sciences of the earth and the oceans, and on a larger community of users in the general populace.

REFERENCES

Apel, J. R., J. R. Proni, and R. L. Charnell, "Observations of Oceanic Internal and Surface Waves Using Remote Sensing Techniques," J. Geophysical Research (to be published), 1974.

Apel, John R., and Joseph W. Siry, "Earth and Ocean Physics Applications Program (EOPAP) Ocean Dynamics Program," *SEASAT-A Scientific Contributions*, NASA, 1974.

Baer, Ledolph, "Comments on Potential SEASAT Applications," *SEASAT-A Scientific Contributions*, NASA, 1974.

Bowin, Carl, "Comment on Satellite Altimeter," *SEASAT-A Scientific Contributions*, NASA, 1974.

Bryan, Kirk, "Measurements of Transient Currents in Mid-Ocean by Altimetry," *SEASAT-A Scientific Contributions*, NASA, 1974.

Byrne, H. Michael, and William O. VonArx, "Geostrophic Current Investigations SEASAT," *SEASAT-A Scientific Contributions*, NASA, 1974.

Campbell, W. J., "SEASAT and Polar Ice," *SEASAT-A Scientific Contributions*, NASA, 1974.

Chen, Davidson, "Geodetic Corrections and Related Information from Oceanographic Measurements Made by SEASAT-A," *SEASAT-A Scientific Contributions*, NASA, 1974.

Chovitz, Bernard H., "Scientific Value of SEASAT for Geodesy," *SEASAT-A Scientific Contributions*, NASA, 1974.

Hansen, Donald V., Deep Sea Research, *17*, 495-511, 1970.

Hansen, W., Dtsch. Hydr. Z., *2*, 44-51 (1949).

Hendershott, M., and W. Munk, "Tides," Ann, Rev. of Fluid Mech., 205-224, 1970.

Hendershott, M. C., W. H. Munk, and B. D. Zetler, "Ocean Tides from SEASAT-A," *SEASAT-A Scientific Contributions*, NASA, 1974.

Hoge, Frank E., "Expected SEASAT-A Scientific Results," *SEASAT-A Scientific Contributions*, NASA, 1974.

Kaula, William M., "Benefits to the Study of Oceanic Tectonics Expected from SEASAT-A," *SEASAT-A Scientific Contributions*, NASA, 1974.

Kellogg, William W., "Satellite Observations of Weather and Climate," *SEASAT-A Scientific Contributions*, NASA, 1974.

Lusignan, B., "A Microwave Occulation Experiment on the Nimbus F Meteorological Satellite," Stanford Electronics Laboratory Proposal No. RL 3-69, January 1969.

Mourad, A. George, "Civil and Scientific Applications of the Geoid," *SEASAT-A Scientific Contributions*, NASA, 1974.

NASA, "Economic Benefits of the SEASAT System," ECON, Inc., 1974.

NASA Earth and Ocean Physics Applications Program, September 1972.

Noble, V., "Exploitation of SEASAT-A Oceanographic Measurements for Navy R&D Applications," *SEASAT-A Scientific Contributions*, NASA, 1974.

Pierson, Willard J., "The Scientific Justification for Obtaining Ocean Wave Data of Various Kinds with SEASAT-A," *SEASAT-A Scientific Contributions*, NASA, 1974a.

Pierson, Willard J., "The Scientific Justification of a Radar Scatterometer and a Passive Microwave System on SEASAT-A," *SEASAT-A Scientific Contributions*, NASA, 1974b.

Robe, R. Q., "Advantages of an Oceanographic Satellite in the Study of Ocean Current Systems," *SEASAT-A Scientific Contributions*, NASA, 1974.

Ruskin, R. E., and R. K. Jeck, Jr., "Navy/NRL Requirements for Sea Surface Wind Measurements on SEASAT-A," *SEASAT-A Scientific Contributions*, NASA, 1974.

Shemdin, O. H., "On the Remote Sensing of Directional Wave Spectra and Surface Winds," *SEASAT-A Scientific Contributions*, NASA, 1974.

Sherman, John W., III, and P. Krishna Rao, "Microwave Measurement of Sea Surface Temperature," *SEASAT-A Scientific Contributions*, NASA, 1974.

Siry, Joseph W., "A Geopause Satellite System Concept," Space Science Reviews, *14*, 314-341, 1973a.

Siry, Joseph W., "Gravimetric Geodesy and Sea Surface Topography Studies by Means of Satellite-to-Satellite Tracking and Satellite Altimetry," Geophys, J. R. Astr. Soc., in press, 1973b.

Smith, Samuel L., III, "Potential Contributions of SEASAT-A to Geodetic Science," *SEASAT-A Scientific Contributions,* NASA, 1974.

Stewart, Robert H., "Satellite Measurements of Ocean Waves," *SEASAT-A Scientific Contributions,* NASA, 1974.

Stommel, Henry, "Studies in Oceanography," 53-58, 1964.

Sturges, W., "Physical Oceanography from Satellites: Currents and the Slope of the Sea Surface," *SEASAT-A Scientific Contributions,* NASA, 1974.

Teleki, P. G., "Expected Scientific Yield of SEASAT-A and Its Application to Corps of Engineers Programs," *SEASAT-A Scientific Contributions,* NASA, 1974.

Weeks, W.F., "SEASAT and Floating Ice," *SEASAT-A Scientific Contributions,* NASA, 1974.

TABLE 1–CAPABILITY OF SEASAT-A IN MEETING USER REQUIREMENTS

PHYSICAL PARAMETER	INSTRUMENTS	RANGE	PRECISION	RESOLUTION OR IFOV	TOTAL FOV	COMMENTS
Wave Height, $H_{1/3}(x,y)$	Pulse Altimeter	1.0 – 20 m	±0.5 m or ±10%	2x7 km spot	2-km swath	along subsatellite track only
Directional Wave Spectrum $S(\lambda,\Theta,x,y)$	Imaging Radar (2-D transform)	S: unknown λ: 50-1000 m Θ: 0-360	S: --- λ: ±10% Θ: ±10°	50-m resolution	10 x 10 km squares	global samples at 500-km intervals
Surface Wind Field, U (x,y)	Scatterometer	U: 3-25 m/s Θ: 0-360	±2 m/s, ±10% ±20°	≤ 50 km spot	two 450-km swaths	global, 36 hrs (low speeds)
	μW Radiometer	U: 10-50 m/s Θ: unknown	±2 m/s, ±10% —	≤ 100 km spot	900-km swath about nadir	global, 36 hrs (high speeds)
Surface Temperature Field, $T(x,y)$	IR Radiometer	-2° to +35°C	±¼° - 1°C	1-7 km IFOV	1500-km swath about nadir	global, 36 hrs (clear air only)
	μW Radiometer	0° to 35°C	±1.5°C	100 km spot	900-km swath about nadir	global, 36 hrs (clouds & lt. rain)
Geoidal Heights, $h(x,y)$ (above reference ellipsoid)	Pulse Altimeter	7 cm - 200 m	7 cm	2x7 km spot	18-km spacing along equator	sampled throughout one year
Sea Surface Topography, $\zeta(x,y)$ (departures from geoid)	Pulse Altimeter	7 cm - 10 m	±7 cm	2x7 km spot	2-km swath	along subsatellite track only
Oceanic, Coastal, & Atmospheric Features (Patterns of waves, temp., currents, ice, oil, land clouds, atmospheric water content)	Imaging Radar	high resolution	all weather	25 m	100 km	sampled direct or stored images
	IR Radiometer	high resolution	clear air	1-7 km	1500-km swath	broadly-sampled images
	μW Radiometer	low resolution	all weather	15-100 km	900-km swath	global images

TABLE II

Related Discipline Studies	PHENOMENA OBSERVED								
	Waves								
	Ht.	Spec.	Imag.	Winds	Temp.	Ice	Tides	Currents	Geoid
Sea-Air Interactions									
Wave generation	X	X	X	X					
Heat transfer					X	X		X	
Sea Interactions									
Wave field evolution	X	X	X						
Wave-wave interactions	X	X	X						
Internal wave generation	X	X	X						
Wave trapping by currents	X	X	X					X	
Wave refraction by currents	X	X	X					X	
Sea-Coast Interactions									
Refraction	X	X	X						
Diffraction	X	X	X						
Planetary Oceanography									
Circulations								X	
Boundary currents					X			X	
Mid-Ocean Currents								X	
Inter-hemisphere Interactions								X	
Ice Fields									
Structure						X			
Dynamics						X			
Solid Earth Physics									
The Gravity Field									X
The Lithosphere									
Structure							X		X
Dynamics							X		X
Ocean Rise Crests							X		X
Ocean Rise Flanks & Volcanism							X		X
Continental Shelves							X	X	X
Subduction Zones							X		X
Marginal Basins							X		X
The Asthenosphere									
Structure							X		X
Dynamics							X		X
Convective Cells							X		X

TABLE II – Continued

Related Discipline Studies	PHENOMENA OBSERVED								
	Waves								
	Ht.	Spec.	Imag.	Winds	Temp.	Ice	Tides	Currents	Geoid
Meteorology									
The Reference Surface				X					
Heat Transfer					X	X		X	
Fronts	X	X	X	X	X			X	
Storms	X	X	X					X	
Planetary Meteorology									
Inter-tropical Convergence Zone	X	X	X	X	X			X	
Inter-hemisphere Interactions	X	X	X	X	X			X	
Polar Regions									
The Southern Ocean	X	X	X	X	X	X		X	
Climatology									
The Reference Surface				X					
Heat Transfer					X	X		X	
Planetary									
Inter-tropical Convergence Zone				X	X			X	
Inter-hemisphere Interactions				X	X			X	
Polar Regions				X	X	X		X	
The Southern Ocean				X	X	X		X	

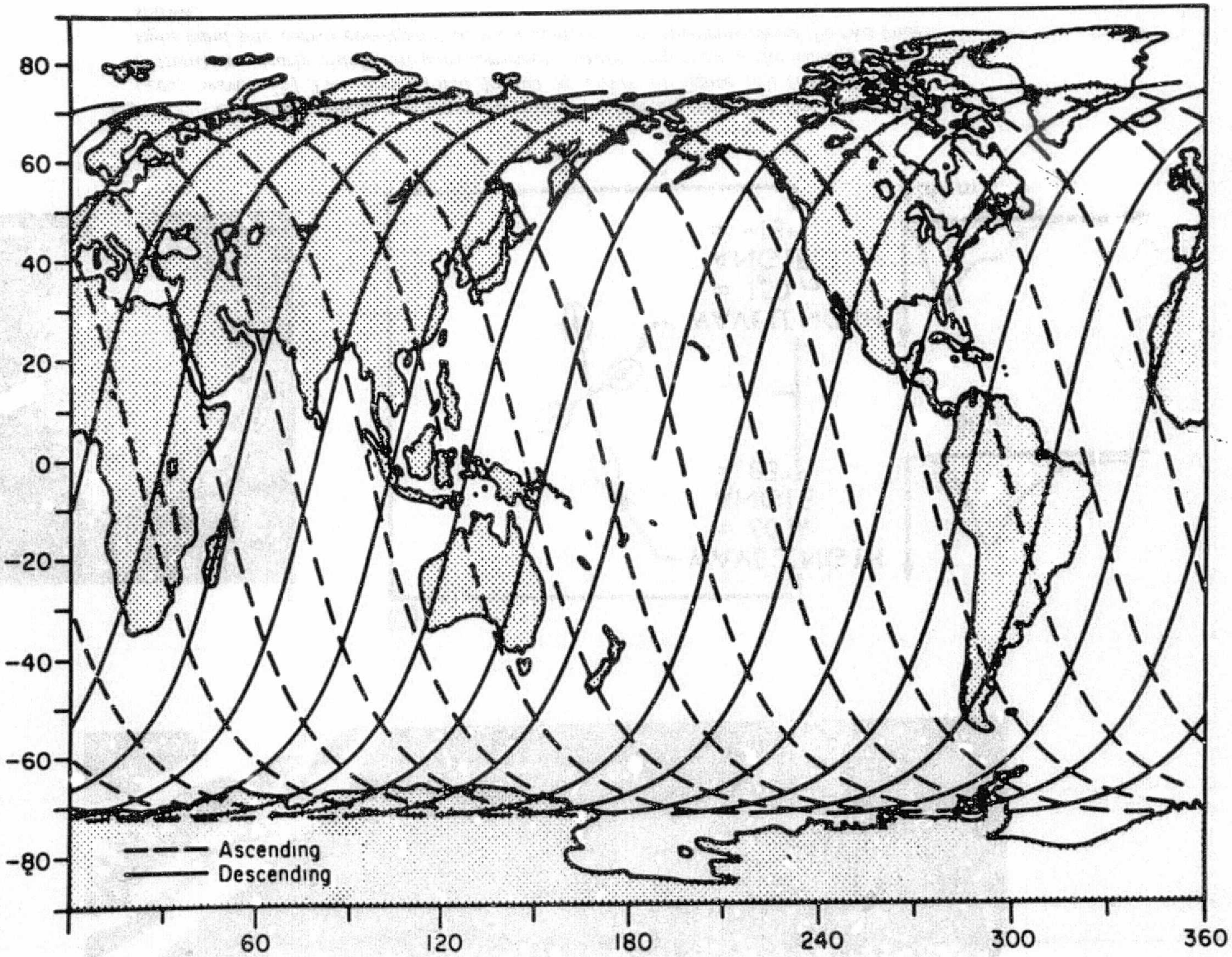


Figure 1.– SEASAT-A orbital ground track during one day.

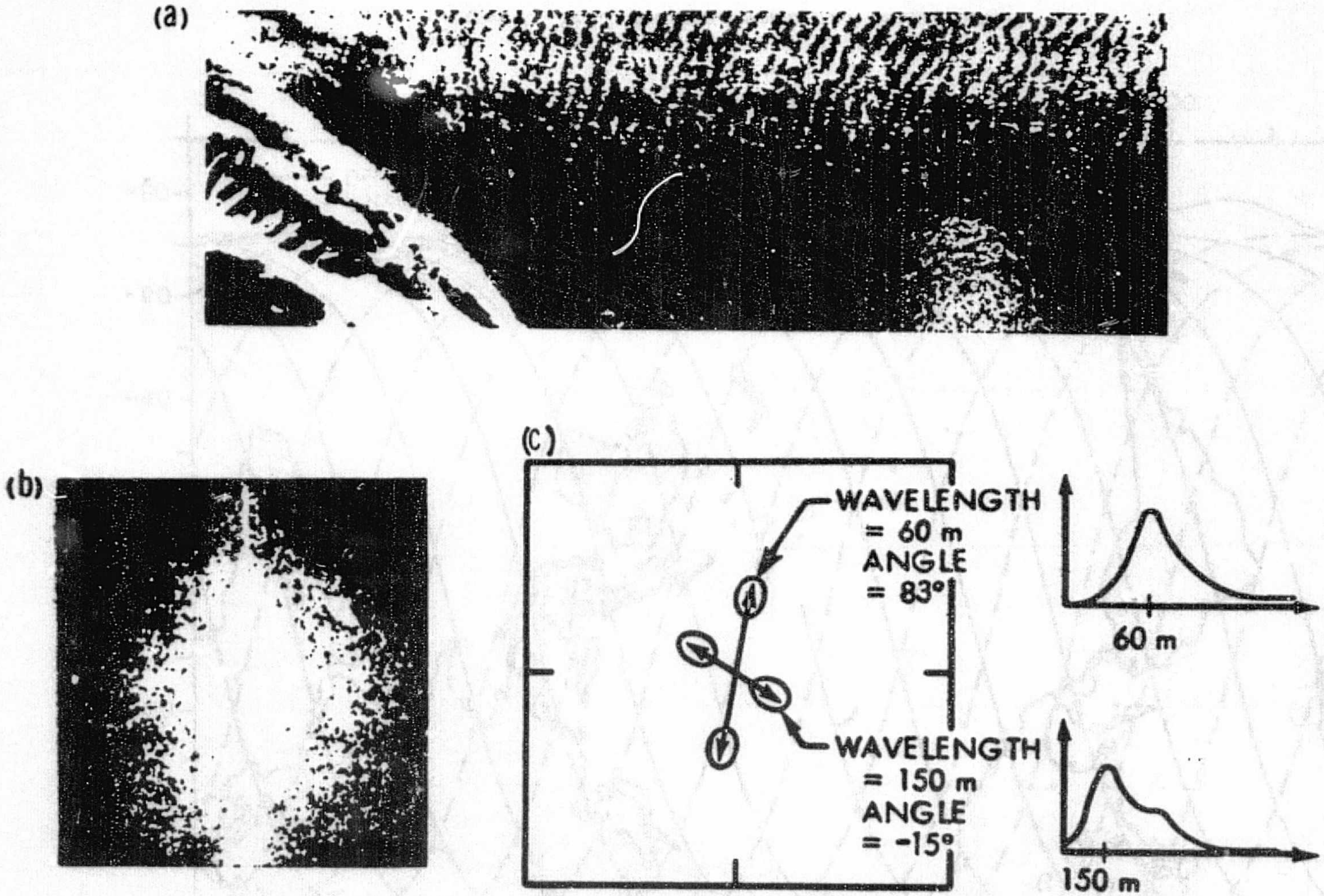


Figure 2.– Ocean wave image and wave spectrum from imaging radar. (a) Radar image of ocean waves; (b) Two dimensional fourier spectrum of figure (a); (c) Two wave patterns are clearly visible, the axes correspond to the frequency of the wave. The two right hand side curves correspond to the intensity of the spectrum along the two lines shown.

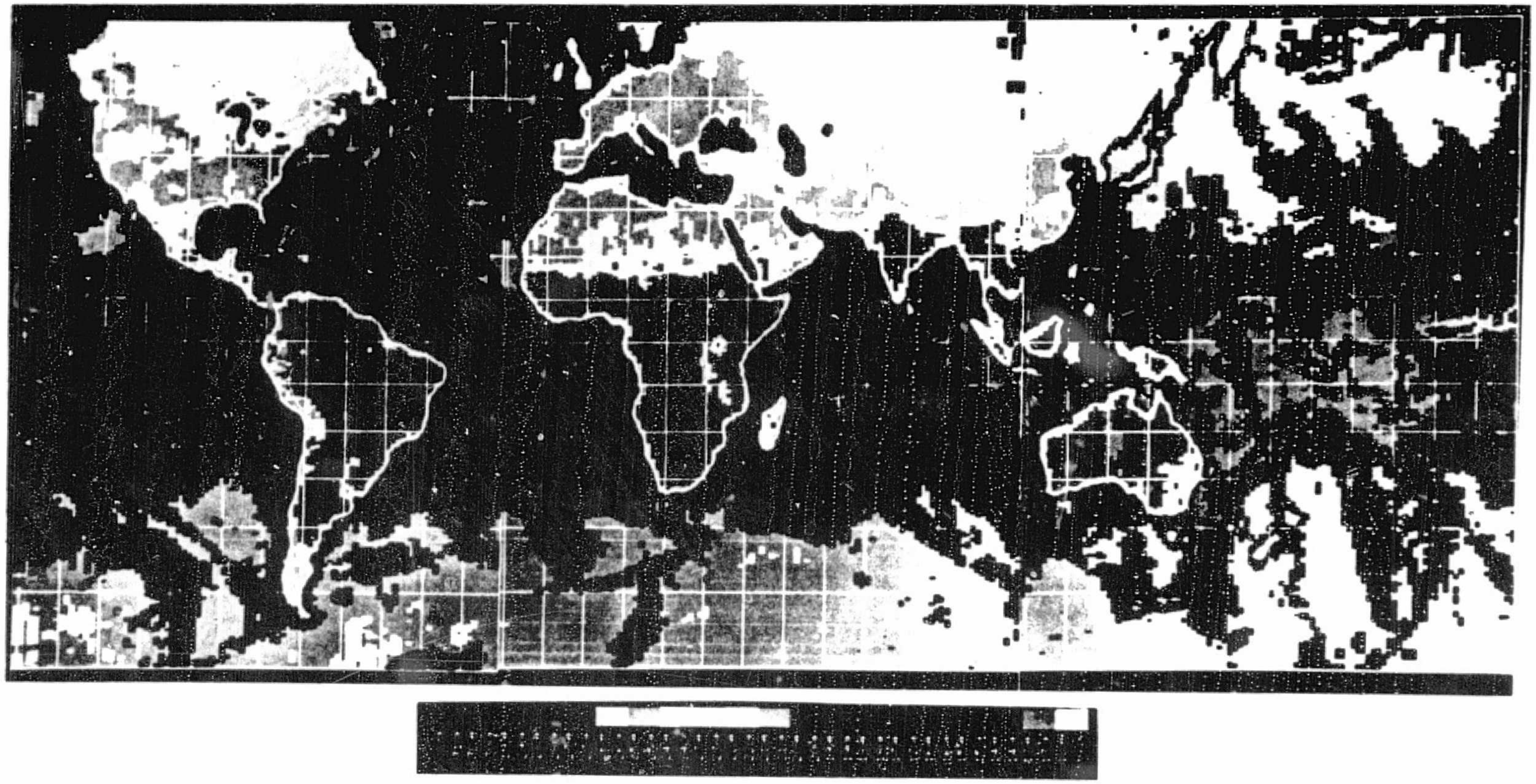


Figure 3. — Radio brightness of the world; Nimbus-5 electrically scanned microwave radiometer (λ= 1.55 cm). January 12-16, 1973.

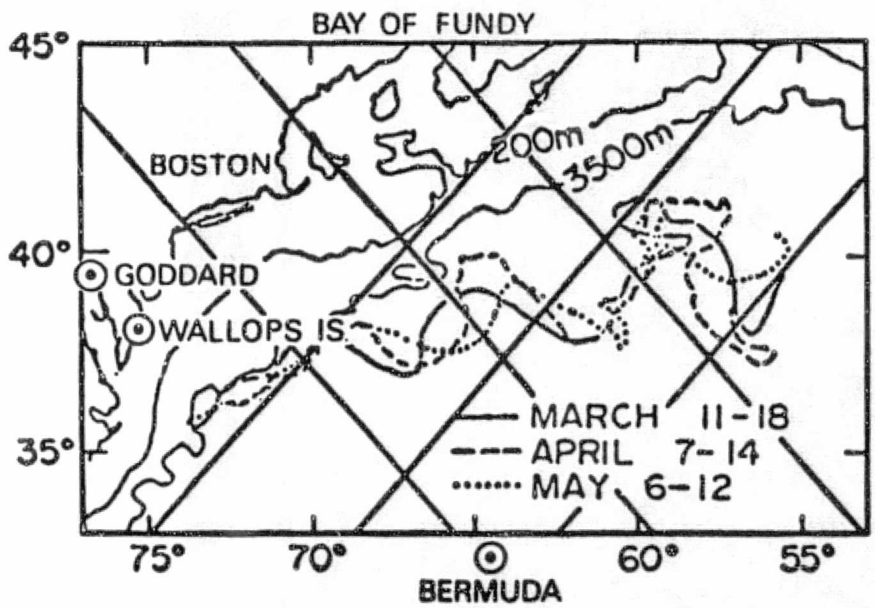

BAY OF FUNDY
45°
40°
35°
BOSTON
200m
3500m
GODDARD
WALLOPS IS.
MARCH 11-18
APRIL 7-14
MAY 6-12
75°
70°
60°
55°
BERMUDA

Figure 4.

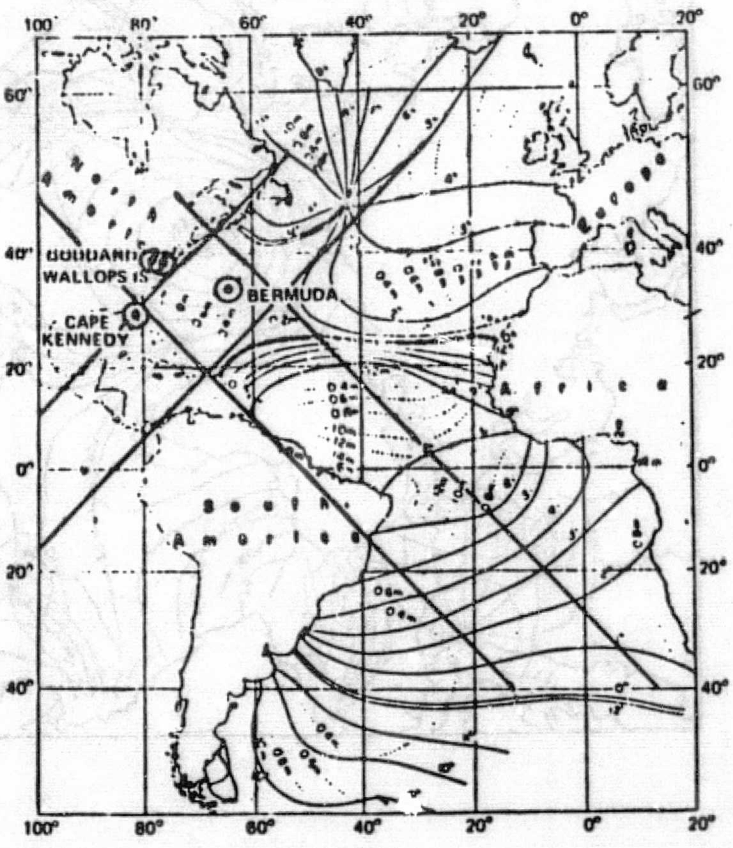

100°
80°
60°
40°
20°
0°
20°
60°
40°
20°
0°
20°
40°
WALLOPS IS.
BERMUDA
CAPE KENNEDY
Africa
South America

Figure 5.

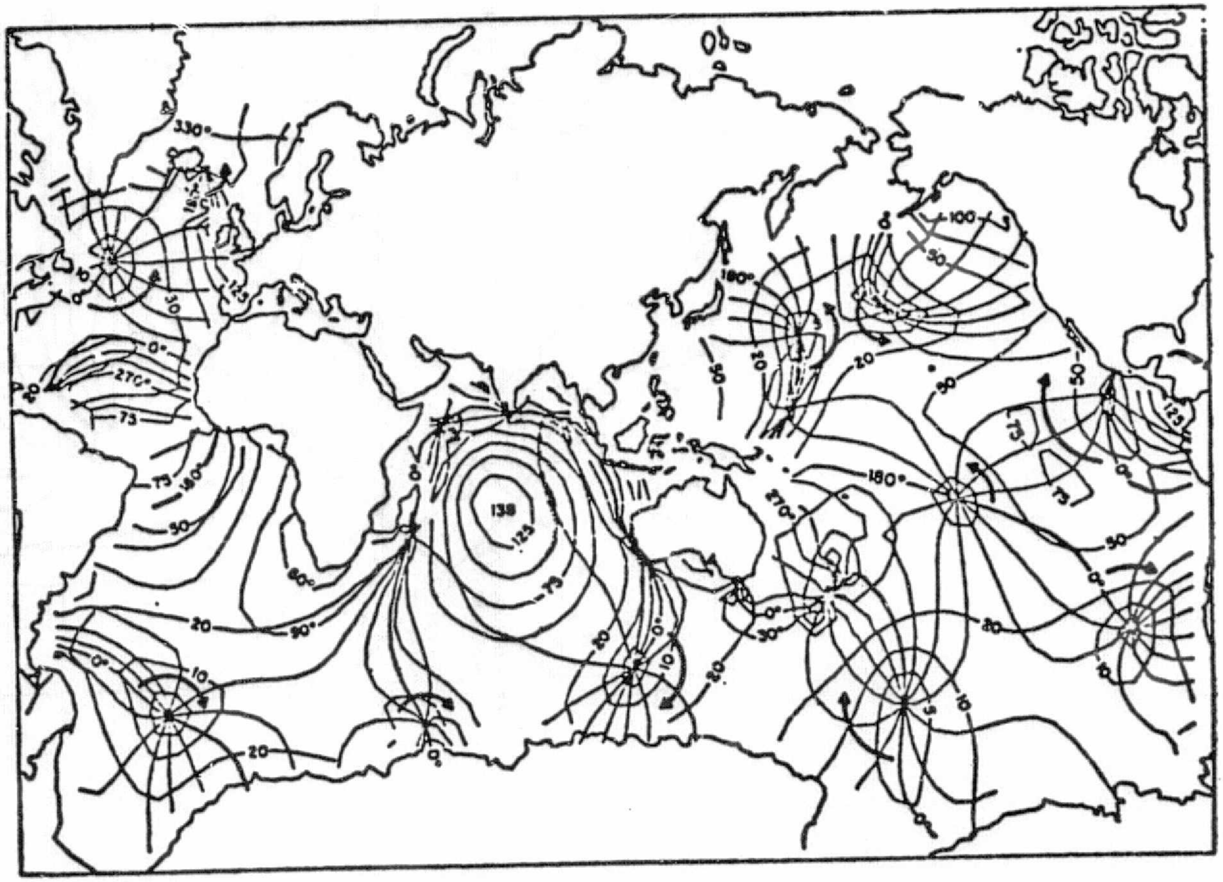


Figure 6.

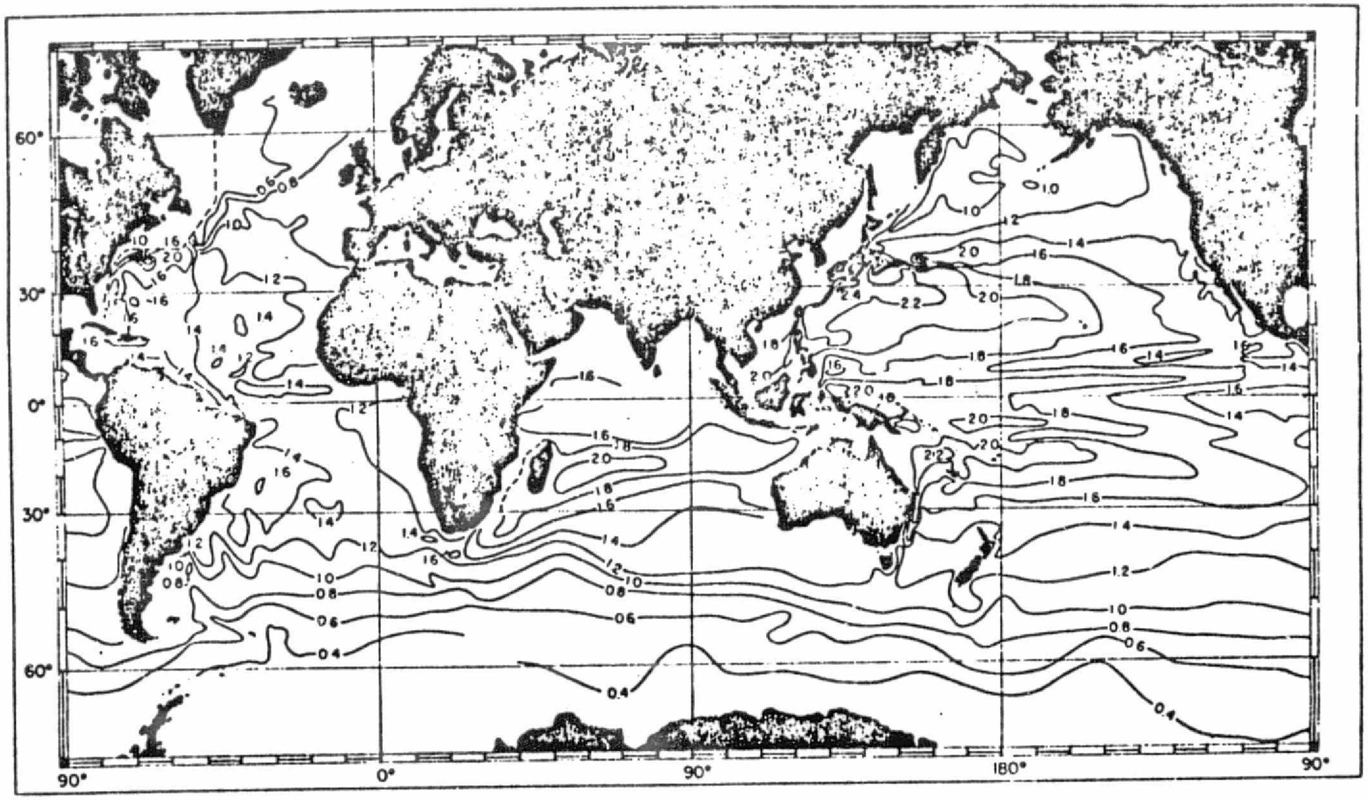


Figure 7.

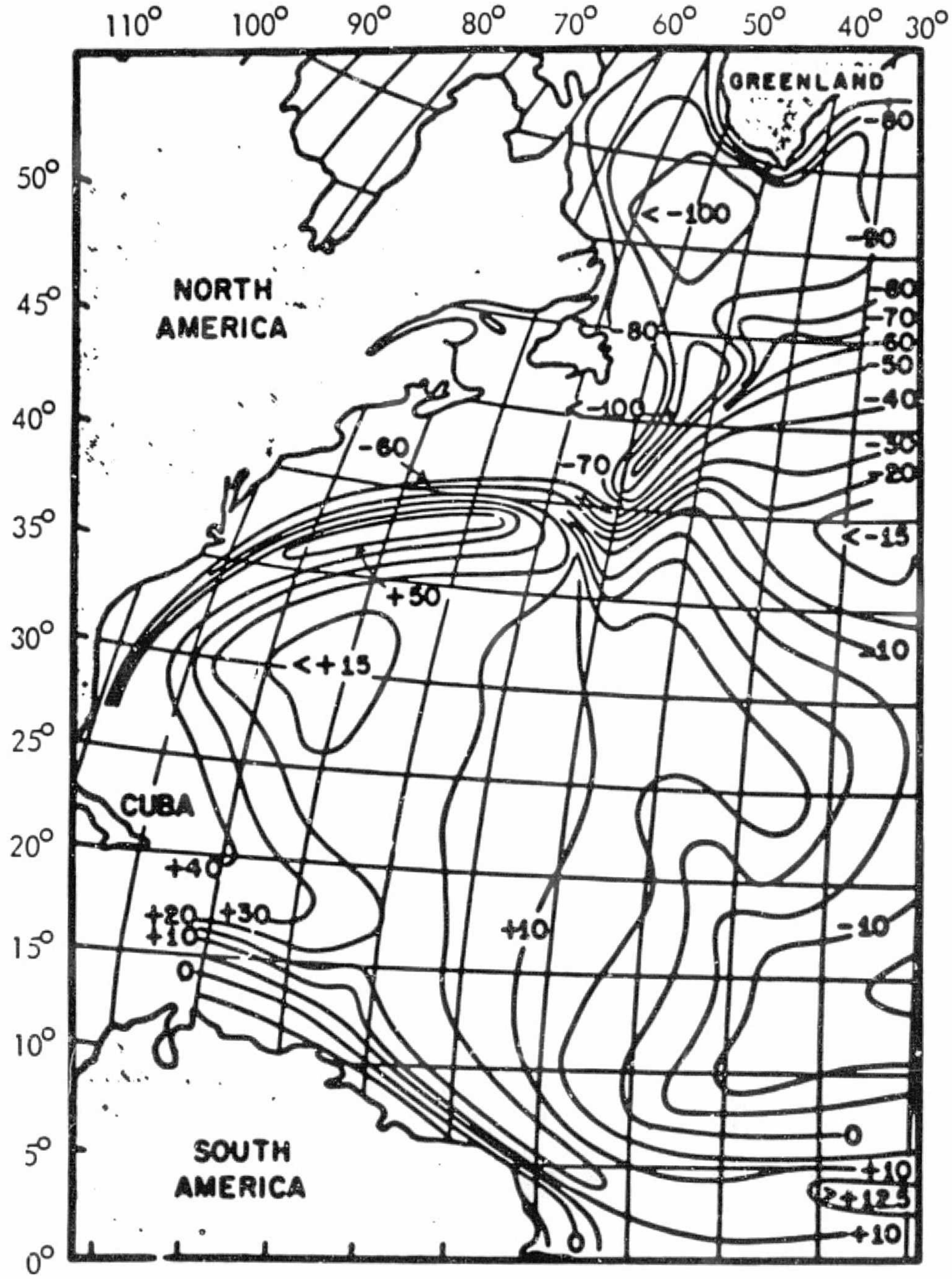


Figure 8. Sea surface topography in the western Atlantic (elevations in centimeters).

Figure 9.

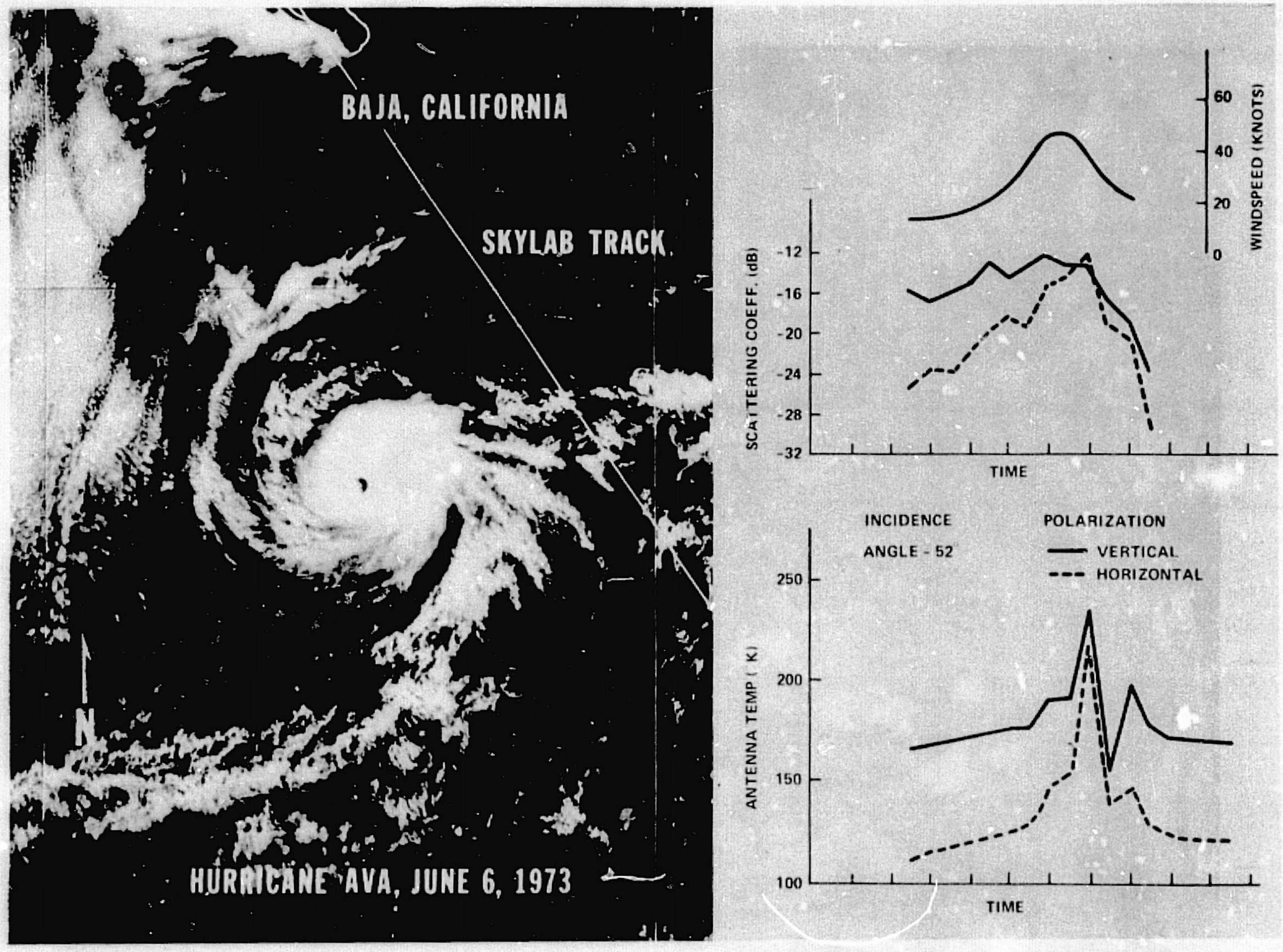


Figure 10.– Hurricane Ava observations (June 6, 1973).

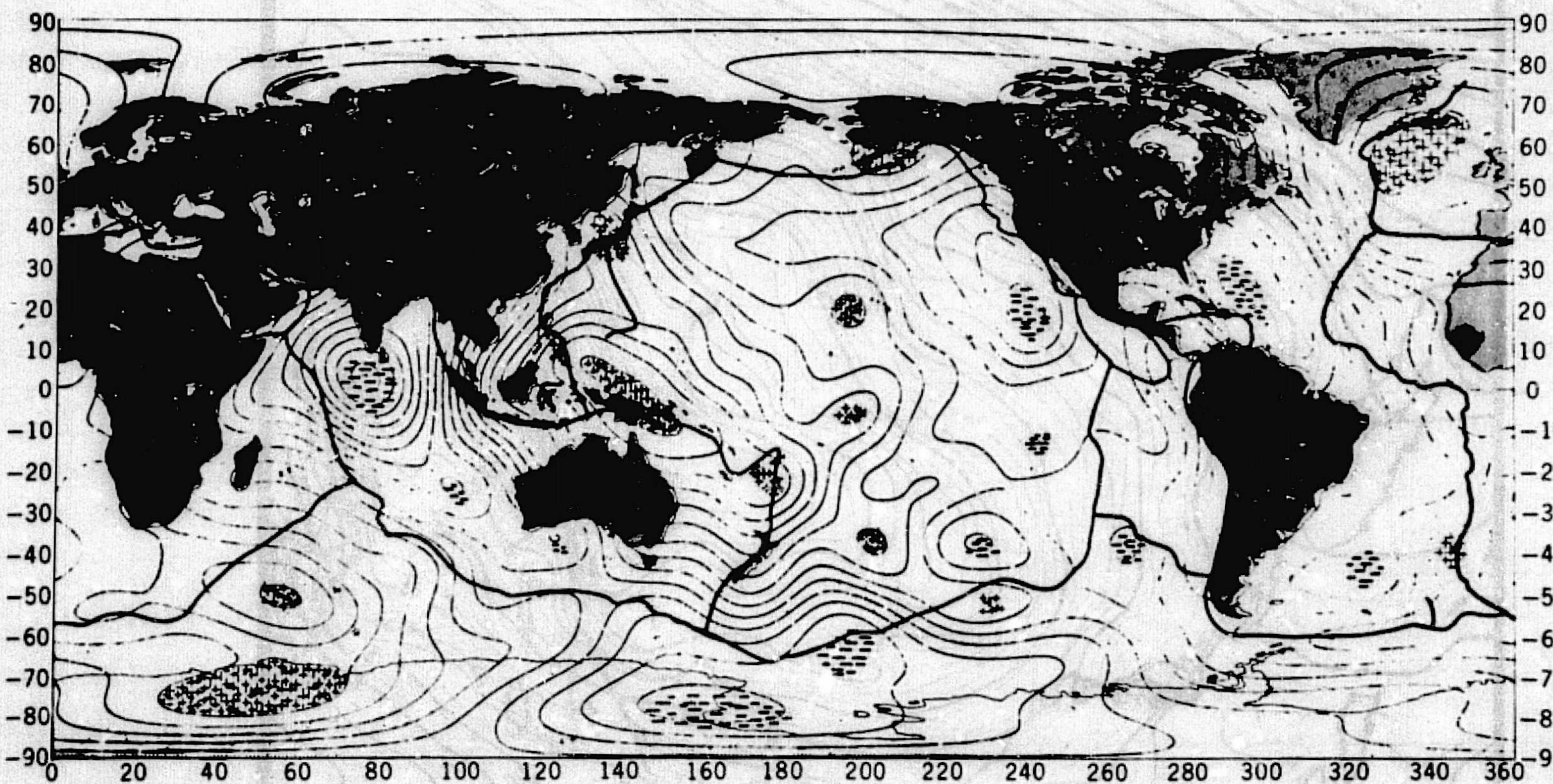


Figure 11.– NASA Goddard Space Flight Center Earth Model 4 (GEM - 4). Geoid Heights: Contour interval, 2 meters; Earth radius, 6378.142 km; l/f = 298.255; gravity field (16x16); GM = 3.98600) x 10^5 km^3/sec^2. This field is derived from a combination of satellite tracking and surface gravity data. Reference GSFC Rept X-592-72-476.

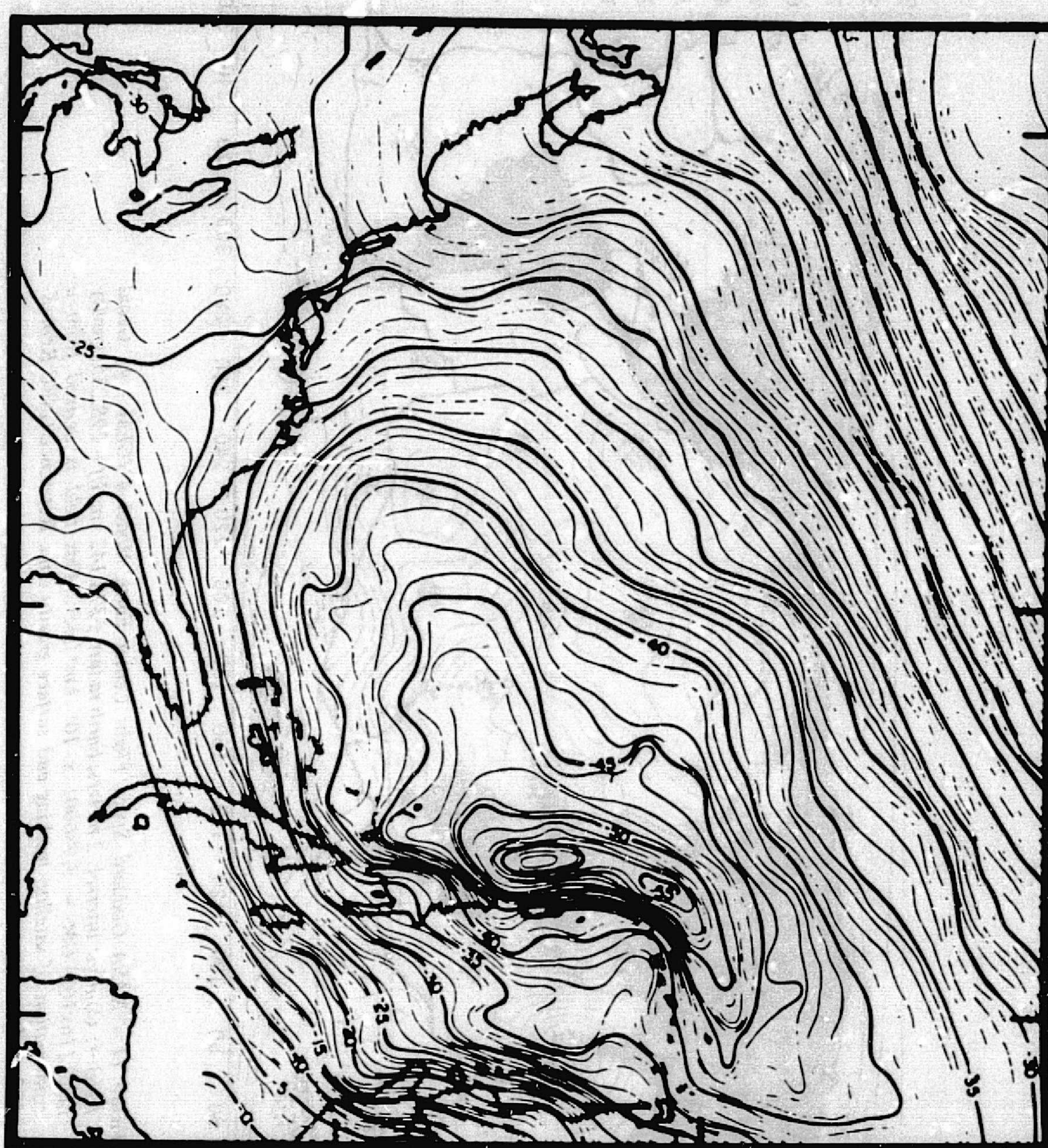


Figure 12.–Geoid in the western Atlantic (elevations in meters).

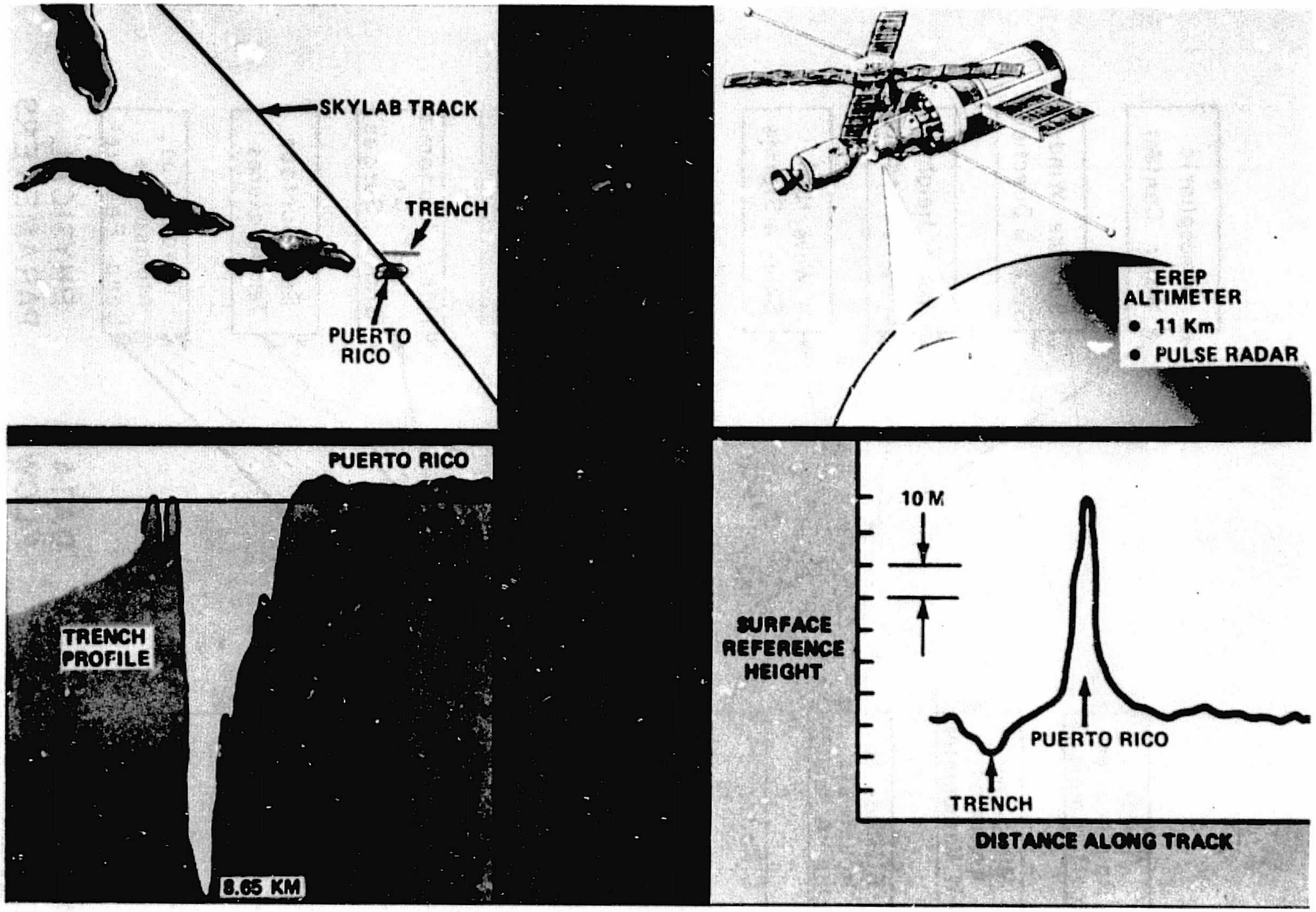


Figure 13.– Geoidal studies, Puerto Rico Trench.

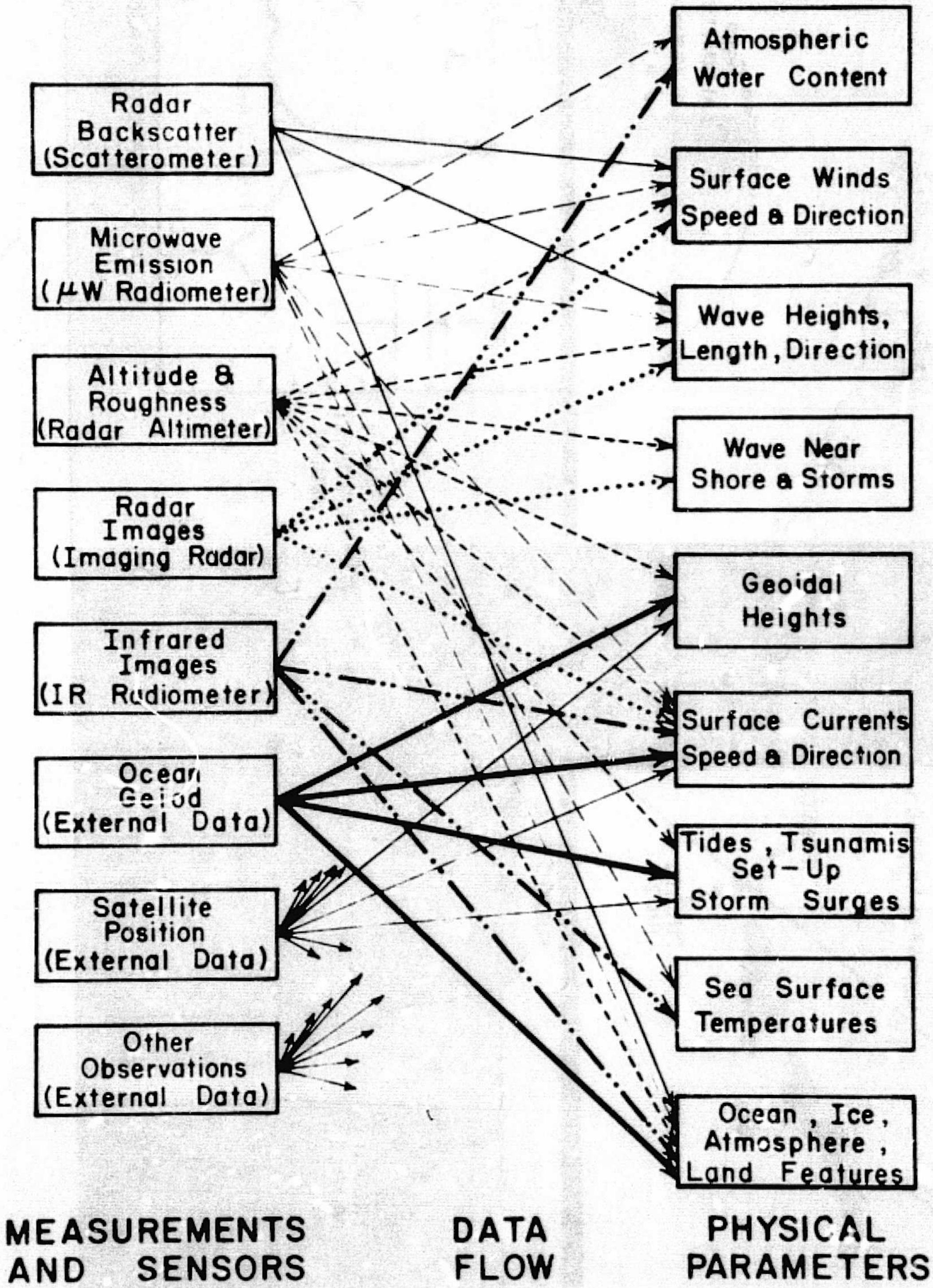


Figure 14.–Relationships between SEASAT-A instruments and physical parameters.

II. SEASAT-A SCIENTIFIC CONTRIBUTIONS

N76 11484

COMMENTS ON POTENTIAL SEASAT APPLICATIONS

Ledolph Baer
Lockheed Ocean Laboratory
Lockheed Missiles and Space Company
San Diego, California

A review of the expected capabilities for SEASAT-A (*NASA*, 1974) as summarized in Table I suggests a number of practical industrial and commercial applications for the resulting data. Some of these were summarized in the referenced document and are reproduced here as Table II. The purpose of this letter is to expand upon this tabulation so as to better show the potential benefits with emphasis on the activities of private oceanographers.

Oceanographic data are used for a variety of industrial and commercial purposes. These data are primarily provided to the users either directly by government agencies such as NOAA (for example: NOS charts and National Weather Service forecasts) or indirectly through private consultants. At present the data are gathered by government agencies, private consultants, and the users themselves.

The types of projects and programs for which the data are needed, the kinds of data, and the applicability of SEASAT can be illustrated by examples of three types of activities as follows:

Design of Offshore Systems (such as the Texas Towers used for petroleum production, harbor design, mining systems, offshore power plants, and ship design).

This application needs probabalistic estimates of the environment which requires many years of data—especially winds, currents, waves, and ice. Present methods of providing this data include scaling winds from historical weather maps (such scaling is often in error by 100%), estimating currents from considerations of winds (accuracy unknown) and the NOS tidal computations, and hindcasting the waves from the winds (with probable errors of the order of 25%).

As a measure of the economic importance for such information it may be pointed out that the petroleum companies as a group have already bought about \$1.5 million in consultant services to describe the environment in the Gulf of Alaska where leasing has not yet begun. There have also been significant in-house efforts. This will be augmented by commissioning studies for each specific area before drilling and again before designing permanent platforms.

The SEASAT should measure most of the parameters needed for such studies however, it and successor systems would have to operate for many years before the artificialities of hindcasting can be eliminated. A minor inadequacy of the SEASAT would be the lack of geographical resolution in measuring the wave spectrum. This is a problem because most such structures are in relatively shallow water where bottom topography affects the waves. Such problems can be skirted, however, in the same way that they are handled at present during a typical hindcasting procedure. Waves are hindcast for open ocean conditions then corrected by a theoretical estimate of the effects of the bottom for the particular location, direction of propagation, and wavelength of the waves.

The SEASAT should improve the quality of the hindcasting in the deep water through research activities, through providing a calibration of a hindcasting technique in a particular area, through eliminating the need for hindcasting eventually, and through providing better surface wind fields. It should also

PRECEDING PAGE BLANK NOT FILMED

provide much useful information on wind, current, and ice.

Offshore Operations (such as oil drilling and production, mining, salvage, and pollution cleanup).

These operations depend upon short term forecasts which are presently marginal at best. A mobile drilling rig can only be positioned when the waves and winds are relatively low. A drill hole cannot be reentered in high waves. Resupply is limited by the weather and wave conditions. Extreme storm conditions require capping and temporary abandonment of oil rigs.

Since the costs of most offshore operations are quite large (cost of drill ships are tens of thousands of dollars per day), an incremental improvement in forecasting so that the operations could be planned more efficiently would be beneficial.

SEASAT should be particularly useful for wave forecasting. It should provide good wind information on which the forecast is based. It should allow improvement of wave forecasting techniques through research. It should provide a good estimate of the directional spectrum of the waves over the entire open ocean area. Thus, the forecasting is simplified to that of propagating swell from its source and making a short range forecast in the immediate vicinity of the operation.

Disposal Operations (such as ocean dumping, sewage outfall operations, and industrial process outfalls).

Besides the usual problems of establishing design criteria, recent pollution and environmental protection legislation and regulation requires detailed monitoring on a continuing basis. This monitoring usually includes both physical and biological observations and requires both surface and subsurface measurements. Parameters of importance include currents, waves, winds, tides, and thermal structure. At present most of this monitoring is carried out on a weekly to seasonal basis using ships. Surface thermal fields are often monitored by infrared measurements from low flying airplanes. However, there is a strong present move toward almost continuous observation through use of buoys in addition to the ship and airplane based studies.

The costs for this monitoring in the SEASAT time frame cannot now be predicted because of the rapid extension of the requirements. However, in the recent past some individual utilities have had to spend upwards of $1 million a year for monitoring of their coastal cooling water effluent fields. On a national basis such costs will certainly be in the hundreds of millions or more.

The SEASAT as presently formulated can aid in this monitoring but it could do much more. We need thermal mapping with an accuracy of about 0.5°C of the entire coastal zone of the United States on a scale of the order of 50-100 meters at least every few days. Such measurements can only be taken efficiently by satellite. Modification of the plans for SEASAT to meet this requirement should be considered.

The primary application of the planned SEASAT capabilities should be in the areas of providing a general large scale environmental description of such parameters as waves, winds, and currents. Thus, these would then not need to be measured as much at each site. In the case of dumping, SEASAT observations and forecasts based thereon would provide a potential basis for optimum scheduling.

CONCLUSION

A few generalizations about the usefulness of SEASAT can be made from these three examples though they certainly are not all inclusive.

1. The SEASAT would be useful for most of the work that private oceanographers and others do in support of industrial and commercial activities.

2. The SEASAT would be more useful if greater spatial resolution could be provided.

3. Methods of rapid dissemination of the data will be needed to aid in the forecast type of activities.

4. The longer that SEASAT type satellites are operated the more useful the data will become. Similarly, there is a need to get started as soon as possible.

REFERENCES

Earth and Ocean Physics Applications Program (EOPAP), Ocean Dynamics Program, NASA, 1974.

TABLE I–CAPABILITY OF SEASAT-A IN MEETING USER REQUIREMENTS

PHYSICAL PARAMETER	INSTRUMENTS	RANGE	PRECISION	RESOLUTION OR IFOV	TOTAL FOV	COMMENTS
Wave Height, $H_{1/3}(x,y)$	Pulse Altimeter	1.0 – 20 m	±0.5 m or ±10%	2x7 km spot	2-km swath	along subsatellite track only
Directional Wave Spectrum $S(\lambda,\Theta,x,y)$	Imaging Radar (2-D transform)	S: unknown λ: 50-1000 m Θ: 0-360	S: --- λ: ±10% Θ: ±10°	50-m resolution	10 x 10 km squares	global samples at 500-km intervals
Surface Wind Field, U (x,y)	Scatterometer	U: 3-25 m/s Θ: 0-360	±2 m/s, ±10% ±20°	< 50 km spot	two 450-km swaths	global, 36 hrs (low speeds)
	μW Radiometer	U: 10-50 m/s Θ: unknown	±2 m/s, ±10% --	< 100 km spot	900-km swath about nadir	global, 36 hrs (high speeds)
Surface Temperature Field, $T(x,y)$	IR Radiometer	-2° to +35°C	±¼° - 1°C	1-7 km IFOV	1500-km swath about nadir	global, 36 hrs (clear air only)
	μW Radiometer	0° to 35°C	±1.5°C	100 km spot	900-km swath about nadir	global, 36 hrs (clouds & lt. rain)
Geoidal Heights, $h(x,y)$ (above reference ellipsoid)	Pulse Altimeter	7 cm - 200 m	7 cm	2x7 km spot	18-km spacing along equator	sampled throughout one year
Sea Surface Topography, $\zeta(x,y)$ (departures from geoid)	Pulse Altimeter	7 cm - 10 m	±7 cm	2x7 km spot	2-km swath	along subsatellite track only
Oceanic, Coastal, & Atmospheric Features (Patterns of waves, temp., currents, ice, oil, land clouds, atmospheric water content)	Imaging Radar	high resolution	all weather	25 m	100 km	sampled direct or stored images
	IR Radiometer	high resolution	clear air	1-7 km	1500-km swath	broadly sampled images
	μW Radiometer	low resolution	all weather	15-100 km	900-km swath	global images

TABLE II–BENEFITS DERIVED FROM SEASAT-A DATA

GENERAL	SPECIFIC
Advancement of Knowledge	• Oceanographic, Meteorological, Geodetic and Engineering Science
Protection of Life and Property	
Navigation and Safety at Sea	• Prediction of High Seas, Adverse Currents • Navigation through Ice Fields • More Precise Iceberg Warnings • Decreased Loss of Men and Ships
Warning of Natural Hazards	• More Accurate, Longer-Term Weather Forecasts • Improved Warnings of Storms and Surges • Decreased Tsunami False Alarm Rate
Economic Benefits to the Nation	
Maritime Operations	• Optimum Ship Routing and Scheduling • Reduced Loss of Oil Drilling Rigs • Improved Design of Offshore Structures • Improved Ship Design • Improved Mapping, Charting, and Geodesy
Utilization of Ocean Resources	• Assessment of Biological Productivity • Location of Potential Fisheries • Enhanced Extraction of Oil, Sand, Minerals
Environmental Impact	• Dispersal of Pollutants and Foreign Substances • Improvement in Shoreline Protection
National Defense Posture	• Improved Environmental Forecasts • More Precise Geoidal Model • Enhancement of Other DOD Missions

N76 11485

COMMENT ON SATELLITE ALTIMETER DATA

Carl Bowin
Woods Hole Oceanographic Institution
Woods Hole, Mass.

The accurate delineation of large scale topography of the sea surface is equivalent to surface gravity measurements and hence can be useful for determining mass anomalies in the earth's crust. Satellite altimeter data offer two advantages over normal shipboard gravity meter observations. Firstly, large scale features of several hundred to several thousand kilometer width are transversed quickly by a satellite pass and hence problems of datum levels and instrument drift tend to be minimized. Secondly, orbiting satellites easily cross regions of the earth's surface that are remote and hazardous for surface travel. The southern oceans and the Arctic Ocean are particularly obvious regions in point. Unfortunately, I understand, self-contained data recording for later transmission is not provided on GEOS-C, and hence altimeter information from areas of the earth remote from tracking and receiving stations will not be possible. Such capability should be included in subsequent missions in order to provide important gravity information in remote reaches of the world's oceans.

The altimeter information obtained during the SKYLAB mission instrument testing has already provided useful data on the marine geoid. Our preliminary analysis of geoid perturbations to be expected from seamount structures indicates that the sea surface bumps observed near an island of the Cape Verde group and a seamount off Brazil are valid geoid features. The positive and negative free-air gravity anomaly belts along the continental edge of eastern North America (see Figure 27 in *Emery et al.*, 1970) provide a useful way of comparing the SKYLAB altimeter data with surface ship gravity data because the widths of the gravity anomaly belts are nearly constant but the amplitude varies along their length. SKYLAB mission SL-2 pass 9 crossed the continental margin near Wallops Island, Va., and shows no evident perturbation of the sea surface over the shelf edge where the surface gravity anomaly relief varies from about +20 mgal to -30 mgal, a peak-to-peak relief of about 50 mgal. However, farther south, pass 4 crossing the Blake escarpment shows a sea surface perturbation of about 4 meters relief and the gravity anomalies vary from about +10 mgal to -110 mgal, a peak-to-peak relief of about 120 mgal. From this simple comparison as well as from other considerations it is clear that altimeter observations from satellites will not eliminate the need for surface gravity measurements. In combination, however, they offer an extremely important approach for the study of the shape of the earth, the perturbations of the geoid, and the determination of mass anomalies within the earth.

REFERENCES

Emery et al., "Continental Rise off Eastern North America," The American Association of Petroleum Geologists Bulletin, *54*, 1, 44-108, January 1970.

N76 11486

MEASUREMENTS OF TRANSIENT CURRENTS IN MID-OCEAN BY ALTIMETRY

Kirk Bryan
Geophysical Fluid Dynamics Laboratory, NOAA
Princeton, New Jersey

Most of the discussion of dynamic topography associated with currents has been centered around the Gulf Stream and its well documented meanders. In this note some evidence is put forward that the SEASAT-A altimetry will also be accurate enough to provide some very interesting information on transient currents in mid-ocean areas. The discussion which follows rests on the assumption that the observed currents are largely in geostrophic equilibrium rather than due to local winds.

On its way to the MODE area in the spring of 1973 the British research vessel *Discovery* made a track from east to west along 32°N. The north-south velocity of surface currents along that track is shown in Figure 1. These velocities are obtained by a careful comparison of satellite navigation positions, and dead reckoning using an automatic log attached to the vessel hull. The amplitude of the variations* is 25 cm-s^{-1} and the peak to peak horizontal scale is of the order of 500 km. As a model assume that the velocities are in geostrophic balance

$$V = \frac{g}{f}\frac{\partial h}{\partial x} \tag{1}$$

where V is the meridional velocity, g the gravitational acceleration, f the Coriolis parameter, and h the surface elevation above the equilibrium surface.

The expression (1) can be integrated with respect to x to find the surface elevation. Let

$$V = 25 \sin \left(\frac{2\pi}{L} x\right) \tag{2}$$

Then

$$h = \frac{f}{g}\frac{L\ 25}{2\pi} \cos \left(\frac{2\pi}{L} x\right) \tag{3}$$

For $f = 0.729 \times 10^{-4}\ s^{-1}$, $L = 5 \times 10^7$ cm, $g = 10^3$ cm-s^{-2}, the amplitude of h is 14.5 cm, and the peak to trough variation is double that or 29 cm.

Little is known about the time variability of the current fluctuations shown in Figure 1. If their frequency is low, like the MODE eddies measured west of Bermuda, they could be monitored by measurements made over fairly large intervals of time (of the order of days or weeks). If it turns out that transient currents of this type can be monitored by the SEASAT-A system all over the World Ocean, it would be of tremendous help to gain an understanding of how variable currents interact with the mean observed circulation of the ocean. This is the central problem in physical oceanography at the present time.

*Personal Communication. Dr. John Gould, Institute Oceanographic Science, Wormley, Godalming, Surrey, U.K.

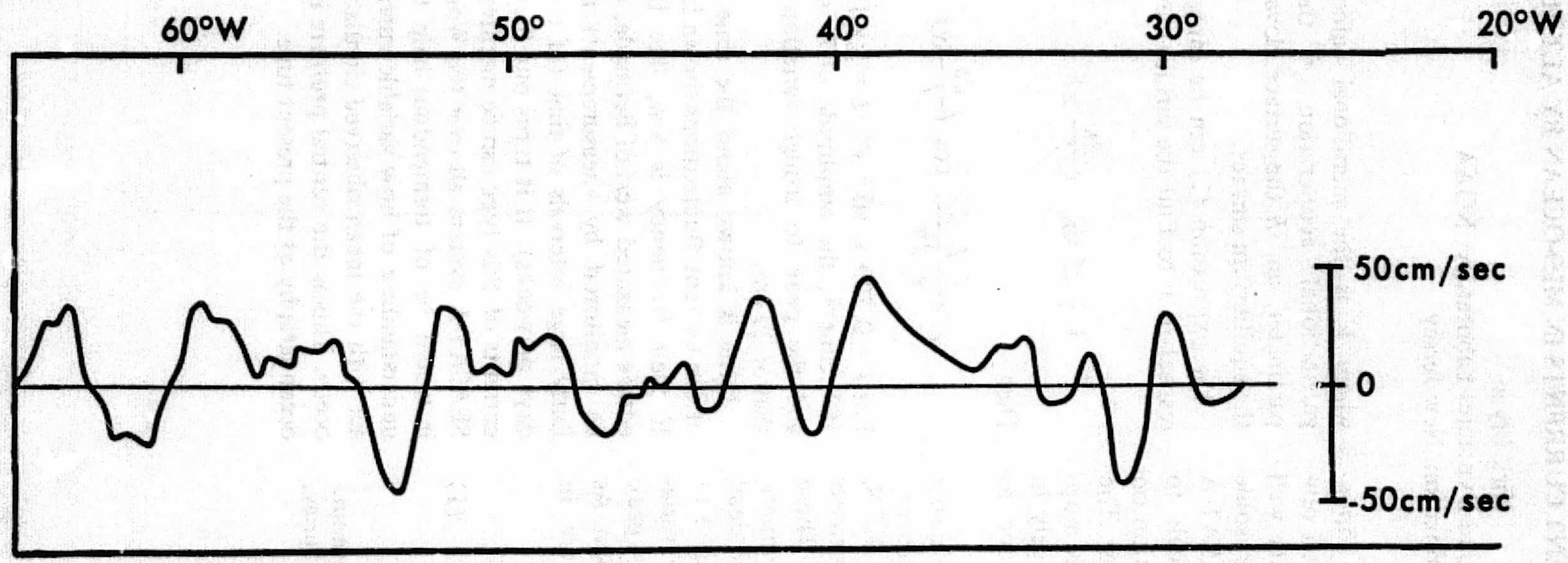


Figure 1.—32°N section. Surface currents from E-M log.

N76 11487

GEOSTROPHIC CURRENT INVESTIGATIONS WITH SEASAT

H. Michael Byrne
National Oceanic & Atmospheric Administration
Atlantic Oceanographic & Meteorological Laboratories
Miami, Florida
and
William O. von Arx
Woods Hole Oceanographic Institution
Woods Hole, Mass.

In the horizontal equations of motion there is an approximate balance between the term of the coriolis force and the term of the absolute horizontal pressure gradients. This relation, often called the geostrophic equation, has been of practical use in estimating the velocities and volume transport of ocean currents.

However, because there has been no method available to date that can measure the *absolute* horizontal pressure gradient but only the *relative* gradients generated by the internal density structure of the ocean. Thus the numbers for velocities and transports have been very much open to question.

By arbitrarily choosing a "level of no motion" one is assuming that the absolute horizontal pressure gradient is zero at that depth. This amount essentially to an arbitrary choice of the constant of integration in the velocity and transport equations.

To define the absolute horizontal pressure gradient in the ocean, it is necessary to measure the configuration of at least one isobaric surface with respect to at least one geopotential surface in each oceanographic section. This given, the absolute *slope* of every other isobaric surface can be reasoned directly from the hydrodynamic equations.

Actual measurement of some absolute horizontal pressure gradient such as that at the sea surface would put these calculations on a firm foundation for the first time.

The SEASAT satellite with a capability of measuring ±1/3 m deviations of sea surface elevations in selected regions will be able, with a sufficient data sample, to estimate time variations of sea surface elevations to approximately that accuracy, and would thus constitute an important first step in measuring the geostrophic surface pressure gradient.

From Table I, we see that this would allow detection of mid-latitude baroclinic or barotropic geostrophic flows with speeds of the order of 1/2 m/s or possibly less.

This would allow a fairly accurate measurement to be made of the flow field of the Gulf Stream, an important western boundary current.

With reasonable coverage every 10 days the SEASAT system would allow oceanographers to investigate the validity of the geostrophic relation for a time varying process, and increase the overall understanding of the dynamical processes inherent in the generation and propagation of meanders along the stream axis.

The measurement of sea surface topography from satellites will also allow tracking of cyclonic cold core rings which are generated by the stream by observing the changes in surface topography due to the currents in the ring (typically 50-200 cm/sec).

Following such rings will provide oceanographers, for the first time, with information on the frequency of generation of these rings, a measure of ring size during their formation and decay, thus providing a better idea of the lifetime of the rings, and perhaps most importantly, an up-to-date (near real time) map of

their position and motion in the western North Atlantic Ocean.

Measurement of the flow of the Gulf Stream and other currents will allow calculations of transport of heat and nutrients to be made more accurately than is currently possible. The continuous measurement of the current and systems if available over several years will begin to make available a measure of fluctuations in the Gulf Stream's currents that has been impossible before.

Many catastrophes of the economic kind, such as failure of the rice crop in Japan, or of the Peruvian anchovy fisheries, or years of unusual numbers of icebergs in shipping lanes, are attributed to fluctuations in ocean currents. Very little is known about such fluctuations. It takes years of careful and expensive conventional observation to produce even a crude description of them. The scientific programs of our oceanographic institutions are not geared to long-term problems of this kind. SEASAT should be able to provide the long-term survey needed to reveal fluctuations in some ocean currents like the Gulf Stream.

Currently there are not sufficient data to permit us to discuss fluctuation of the geography in the Gulf Stream lasting longer than one year. This is because early measurements were made without knowledge of the existence of meanders and rings. Unless allowance can be made for these short perior fluctuations, the longer period variations obtained by plotting the data are not statistically significant.

The area encompassed by the Gulf Stream meander region is so large, and the time scale of variation of the meander so short that it is impossible to adequately measure the dynamical phenomena with anything except a satellite system.

In a more general sense, we must come to terms with the ocean as a large-scale turbulent medium and design experiments to measure the nature of the turbulent processes. SEASAT-A will permit us to begin to investigate these processes.

Therefore, it is not a question of how much better the measurements of ocean dynamics will be from SEASAT; but to say flatly that SEASAT is the only system available in the near future which will be capable of measuring the pressure and motion fields in the whole area reliably, synoptically, and at an affordable cost.

TABLE I—MAGNITUDES OF REGIONAL SEA SURFACE SLOPES PRODUCED BY SYNOPTIC INFLUENCES (ANGLES IN RADIANS)

Equilibrium tidal slopes in mid-ocean.		10^{-10}
Wind set-up in open ocean (Trades)		10^{-7}
Geostrophic slopes in middle latitudes for ordinary speeds of flow	1 cm/sec	10^{-7}
	10 cm/sec	10^{-6}
	100 cm/sec	10^{-5}
Shelf tides; Tsunamis in deep water		10^{-6}
Barometric loading		
Margins of anticyclones		10^{-6}
Cores of extratropical cyclones		10^{-5}
Hurricanes (near eye)		10^{-4}
Wind set-up by coastal gales		10^{-4}
Tidal slopes in embayments and canals		10^{-4}
Bores and surface waves (large but not regional)		

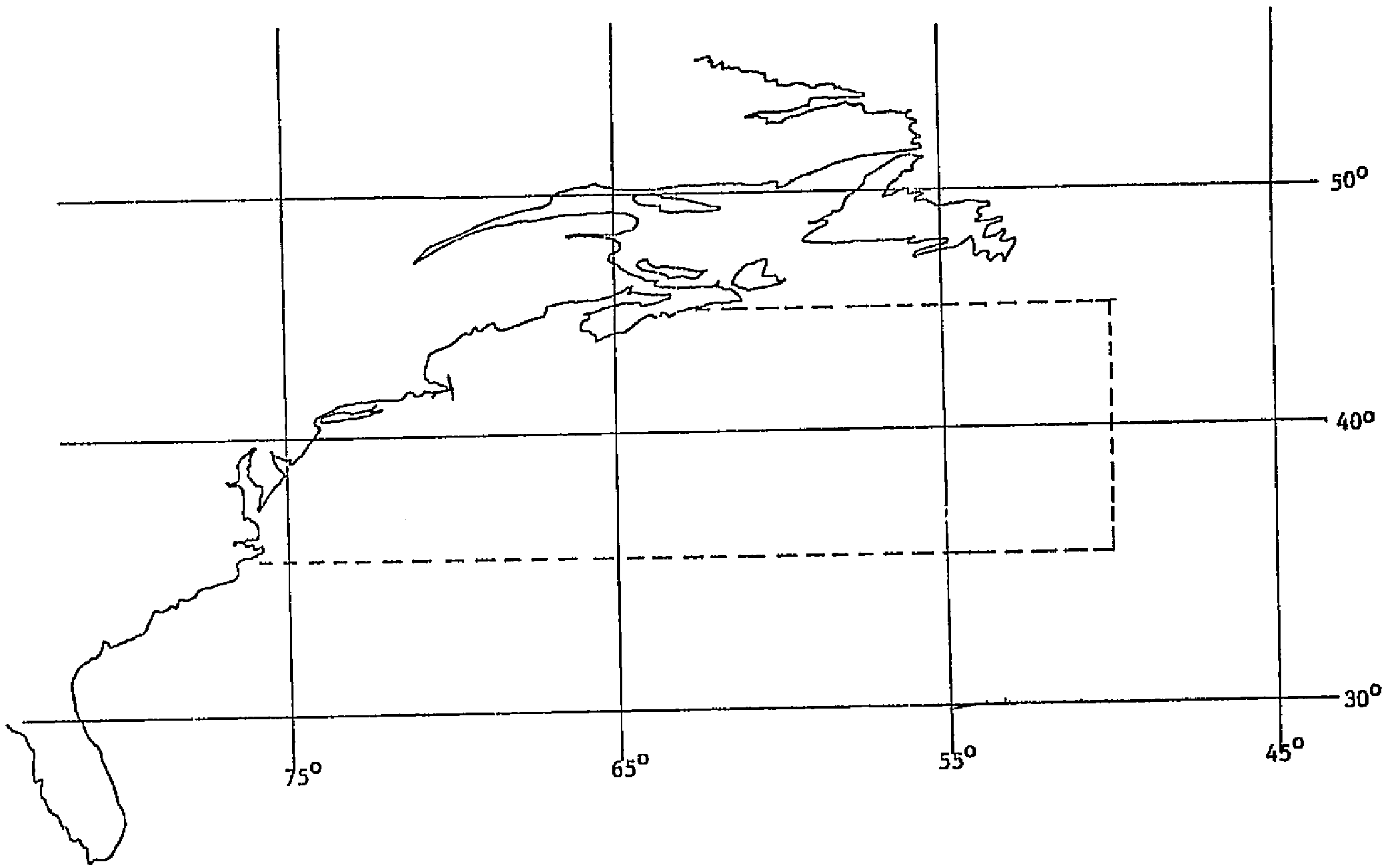


Figure 1.–Gulf Stream meander region.

N76 11488

SEASAT AND POLAR ICE

W. J. Campbell
Ice Dynamics Project, USGS
University of Puget Sound
Tacoma, Washington

When we talk of polar ice we speak of (1) the sea ice canopies that cover large parts of polar oceans and average from one to several meters in thickness; and (2) the polar ice caps, such as Antarctica, Greenland, and Elsmere, that are composed of glacier ice and have thicknesses in the order of several kilometers. Dr. Weeks has addressed the problem of SEASAT in relation to floating ice, therefore I would like to talk about SEASAT in relation to ice cap research.

Approximately 87% of all the fresh water that exists on this planet exists in the form of ice in Antarctica and Greenland. Glaciological research in these two areas has been aided greatly by the development of radio echo sounding techniques which have made possible the delineation of the surface and bottom topography along selected lines in these ice masses. Such measurements are fundamentally necessary to test the numerical models of ice flow.

The instrument package for SEASAT-A possesses three tools that could give data greatly needed in ice cap research: the Compressed Pulse Radar Altimeter (CPRA), the Coherent Imaging Radar (CIR), and the Scanning Multifrequency Microwave Radiometer (SMMR). In the following I will discuss certain problems that can be studied with each sensor.

COMPRESSED PULSE RADAR ALTIMETER (CPRA)

Although SEASAT will not pass over Antarctica, it will orbit over a major part of Greenland and the Elsmere Icecap. Accurate profiles of the surface of these icecaps, obtained by surface traverses and aircraft flights, have been obtained only along a few select lines. None of these profiles is as accurate as those that will be obtained from CPRA. SEASAT has the capability therefore of mapping the surface topography of these icecaps to an accuracy never before possible. Not only will these measurements provide very useful data for analyzing the ice flow patterns of the icecaps, but if similar measurements were obtained in the order of 5-10 years in the future a synoptic view of the accumulation pattern of the icecaps could also be obtained. Such highly accurate surface profile measurements could also provide important information on numerous glaciers that SEASAT will orbit over, such as the large piedmont glaciers in southeast Alaska and the large valley glaciers in the Himalayas.

SCANNING MULTIFREQUENCY MICROWAVE RADIOMETER (SMMR)

Images obtained by the ESMR on Nimbus-5 at 19 GHz have shown that the surfaces of Greenland and Antarctica emit a highly complex pattern of surface brightness temperatures. Theoretical work presently underway, in which the ice is treated as a bulk scatterer, indicates that the surface brightness temperature is a function of the crystal size. Therefore, the SMMR could be used to study the surface crystal structure of icecaps and large glaciers. Such measurements on a large scale are capable only by space techniques and are relevant to a large range of glaciological studies. If the surface brightness temperature of icecaps were monitored by SEASAT and subsequently compared to later ones we could assess variations in the surface structure due

to meteorological variations, such as changes in the storm track and cloud distributions.

COHERENT IMAGING RADAR (CIR)

Radar measurements of icecaps and glaciers by Walt Brown of JPL and V. Bogorodsky of the Arctic and Antarctic Research Institute in Leningrad have shown that near sub-surface features can be observed. The Soviet SLAR images of Arctic valley glaciers show that the foliation planes formed in glaciers by seasonal mass supply can be clearly observed through the surface snow cover. Structural patterns in Greenland that seem to be related to surface flow have been observed by Walt Brown along certain selected flight lines, and when CIR images are obtained of Greenland it may be possiole to distinguish between foliation planes and other structural features induced by ice motion.

Both Dr. Weeks and I agree that sequential observations of both floating and glacier ice by the SEASAT CIR, SMMR, and CPRA could provide unique and important data for polar research.

N76 11489

GEODETIC CORRECTIONS AND RELATED INFORMATION FROM OCEANOGRAPHIC MEASUREMENTS MADE BY SEASAT-A

Davidson Chen
Naval Research Laboratory
Washington, D.C.

INTRODUCTION

The oceanographic measurements taken by SEASAT-A are not only applicable to correct altimetry data for the desired geoid but also, as a result, they themselves are useful by-products for basic and applied research in the fields of sciences and engineering, exploratory development in sensor design and measurement techniques, and prediction products for operational fleet support. Among these measurements the important ones are current, sea state, and tides.

Due to the very nature of these measurements, all the information obtained is confined to the surface. However, the ocean environment is a complicated one; the physical processes in the ocean are controlled by both surface and subsurface parameters. These parameters act, interact, and produce the phenomena one actually observes (*Chen*, 1973). Thus the desired phenomena such as currents can be measured directly or inferred from remote sensors (*Huang et al.*, 1972).

The purposes of this report are to identify the parameters of the measurements, which will be used to eliminate temporal environmental biases from geodetic measurements, and also to describe the physical processes involved. The corrected geoid as well as information on current, sea state, and surface temperature field are very important to Naval operations.

PARAMETERS INVOLVED IN OCEANOGRAPHIC CORRECTIONS FOR GEOID

Surface Temperature Field

The earth on which we live is actually a big heat engine; the energy mainly is from the sun. The energy reaches earth by radiation and then subsequently is transported by large scale convection motions (the oceanic and the atmospheric circulations), evaporation, and reflection. In order to improve our understanding of the ocean, a global heat budget and dynamic models are indispensable. Before this can be done the information on surface temperature fields can help to delineate boundaries of large scale motions (*Hollinger*, 1973; *Strong and DeRycke*, 1973) and, also, to delineate the density field which will be used directly to calculate current systems (*Hill*, 1962; *Neumann and Pierson*, 1966). There are both a five frequency scanning microwave radiometer and an infrared imaging radiometer planned to be on-board SEASAT-A for the measurement of surface temperature field (*NASA*, 1973). Although the infrared imaging radiometer has a better resolution, it is inoperative through cloud cover. These two instruments supplement each other in that the infrared imaging radiometer provides calibrations for the five frequency scanning microwave radiometer in the case of clear sky.

Ocean Surface Wind Field

Most currents and ocean waves are generated by ocean surface wind (*Hill*, 1962; *Phillips*, 1969). The five frequency microwave radiometer (*Hollinger*, 1971) as well as microwave scatterometer and imaging radar (*NASA*, 1973) can be used to develop the directional information for ocean wave and surface current analyses.

Sea State

Since most ocean waves are generated by wind (*Phillips*, 1969), the sea state is closely

related to weather conditions. Available data collected by traditional oceanographic methods up to now are limited to shallow water or calm sea cases. But the central problem here is to develop dynamic wave prediction models which include severe storm conditions in the open ocean. Open-ocean sea state measurements will supply a boundary condition to the problem of predicting storm surges at a given coastal area (*Ippen*, 1966; *Neumann and Pierson*, 1966). Since the sea surface is always random, the meaningful specification of the sea state is always in the form of various statistical measurements such as wave spectrum, surface height distribution, etc. On board SEASAT-A a pulse compression radar altimeter, a coherent imaging radar, and/or wave spectrum sensors are used to obtain sea state information (*NASA*, 1973).

OCEANOGRAPHIC CORRECTIONS FOR GEOID

The ocean surface topography measured by the pulse compression radar altimeter and the coherent imaging radar is the sum of geoid and noises. These noises include instrumental variations, atmospheric interferences, sea state, tides, storm surges, and current caused elevation changes. In order to get to the real geoid these noises have to be removed. The atmospheric interferences caused by air and the moisture content can be corrected by atmospheric propagation corrections which will not be discussed here. The oceanographic corrections for the geoid will be listed and discussed briefly in the following paragraphs.

Instrumental Variations of Mean Sea Levels

The electromagnetic mean sea level indicated by the pulse compression radar altimeter is a function of the shape of the transmitted signal, internal electronic system parameters, and the instantaneous statistics of local sea surface elevations (*Yaplee et al.*, 1971). This error or deviation between the measured mean electromagnetic sea level and the real geometric mean sea level can amount to 5 percent of the local wave height. This elevation presents problems of its own when one is talking about the accuracy of the whole system. The corrected mean sea level is the reference level for further corrections to the geoid model.

Sea State

Variations of local sea state appear as a transient signal or noise in the altimeter returns. Therefore the altimeter data can be used in a self-correcting mode to compensate for the effects of sea state variations. After this has been done, the data still contain those low-frequency features such as tide and storm surges and, also, the quasi-permanent features such as current caused elevation change along the major ocean current systems.

Tides

Tides on the earth are caused by the gravitational attractions between the sun and the earth and the moon and the earth. Except at coastal and estuarine regions where tidal effects are magnified, the tidal wave height at some locations in the open ocean can amount to one meter. The characteristics of tidal motion are modified extensively by the bottom topography and the coastal boundaries.

Storm Surges

Because of the large air pressure gradient and wind speeds of a hurricane over a localized region, the sea level can be as high as one meter above the mean sea level. The pile-up of water against the coast under the action of a hurricane can be very high.

Current Caused Elevation Change

Currents in the ocean are generated primarily by wind stress, temperature and density differences, and pressure gradients. The motions are modified by the rotation of the earth, frictional forces, and astronomical forces. In most cases, current and the ocean density structure can be related by the geo-

strophic assumption and, if we further assume barotropic motion, the current can be related directly to the mean sea level slope. Thus, in order to calculate the elevation change caused by the current, the magnitude and direction of the current have to be known first. Studies (*Longuet-Higgins and Stewart*, 1961; *Huang et al.*, 1972; *Phillips*, 1969; *Noble and Yaplee*, 1973) have shown that as waves encounter current, wave characteristics undergo changes due to interactions between waves and current. Henceforth, those changes in wave characteristics in the forms of wave spectra, surface roughness parameters, and wave height distribution can be used to detect currents.

SUMMARY

Various kinds of oceanographic corrections for the geoid have been discussed and described in the previous pages. Determination of an accurate geoid is required to improve the accuracy of inertial guidance systems. It is easy to mention a few examples of the usefulness of those oceanographic corrections to the Naval community. First of all, the information on surface temperature fields can be used in electronic submarine warfare. The information on ocean surface wind fields and sea state can be utilized in operational fleet support and Naval ship design. Locations of seamounts can be detected through mean sea level measurements and these also will aid in underwater warfare.

The most important point of this discussion is in the demonstration that data taken by SEASAT-A can benefit the Naval community as a whole, including fleet operations, research and development aspects of verification of sensor performance, future sensor design, information handling mechanisms, descriptive and predictive ocean models, and better ship design.

REFERENCES

Chen, D. T., Use of Lidar Systems in Measuring Certain Physical Oceanographic Parameters, Proceedings, Symposium on the Use of Lasers for Hydrographic Studies, NASA Wallops Flight Center, 65-69, 1973.

Hill, M. N. (General Editor), The Sea, Vol. I, Interscience Publishers, N.Y., 1962.

Hollinger, J. P., Passive Microwave Measurements of Sea Surface Roughness, IEEE Transactions on Geoscience Electronics, 165-169, 1971.

Hollinger, J. P. Microwave Properties of a Calm Sea, Report No. 7110-2, Naval Research Laboratory, 1973.

Huang, N. E., Chen, D. T., Tung, C. C., and Smith, J.R., Interactions between Steady Non-Uniform Currents and Gravity Waves with Applications for Current Measurements, J. Physical Oceanography, *2*, 420-431, 1972.

Ippen, A. T. (Editor), Estuary and Coastline Hydrodynamics, McGraw Hill, N.Y., 1966.

Longuet-Higgins, M. S., and Stewart, R. W., The Changes in Amplitude of Short Gravity Waves on Steady Non-Uniform Currents, J. Fluid Mech., *10*, 529-549, 1961.

NASA, SEASAT-A Study Task Team Report, 1973.

Neumann, G., and Pierson, W. J., Jr., Principles of Physical Oceanography, Prentice Hall, 1966.

Noble, V. E., and Yaplee, B. S., Progress Report on Environmental Remote Sensing for July 1973 to December 1973, Naval Research Laboratory, 1973.

Phillips, O. M., The Dynamics of the Upper Ocean, Cambridge University Press, 1969.

Strong, A. E., and DeRycke, R. J., Ocean Current Monitoring Employing a New Satellite Sensing Technique, Science, *182*, 482-484, 1973.

Yaplee, B.S., Shapiro, A., Hammond, D.L., and Uliana, E.A., Ocean Wave Height Measurements with a Nanosecond Radar, Proceedings 7th International Symposium on Remote Sensing of Environment, 1879-1893, Ann Arbor Michigan, 1971.

N76 11490

SCIENTIFIC VALUE OF SEASAT FOR GEODESY

Bernard H. Chovitz
National Oceanic and Atmospheric Administration
Rockville, Md.

The essential point for geodesy is the altimetry data which relates directly to geoid heights. This yields the means to obtain information on the geoid on a global scale which is not attenuated by height or by high-frequency averaging. Probably the most important geodetic application of this data is to provide a standard reference surface for the oceans. Let us focus for the moment on those oceanographic phenomena which are primarily time invariant (currents, sea slopes) or are regularly periodic (ocean tides, seasonal temperature variations) leaving out randomly varying effects (sea state, tsunamis). The quantitative identification of the first two sets requires a standard surface to which they can be referred. This surface is naturally the geoid. The problem is somewhat akin to leveling on land which yields the vertical relation of the physical surface to sea level. Over the ocean, we are dealing with much smaller departures, of the order of a meter, and with periodic variations, plus random noise (sea state) to further complicate matters. But just as the problem of leveling is entirely separate from the determination of the geoid, similarly the determination of the sea surface topography is separate from that of the ocean geoid. The former falls in the domain of the oceanographers, the latter in the domain of the geodesists. However, the essential point here is that the reference surface—the geoid—to the desired accuracy must be available to the oceanographers just as it must be available to the levelers on land. Thus, in order to meet oceanographic requirements for information on sea surface topography and to exploit the precision of the SEASAT-A instrumentation, the geoid over the oceans must be known to the same precision. This probably is the prime geodetic objective in connection with the SEASAT-A project: the determination of the geoid to the accuracy needed to serve as a reference surface for the sea surface topography. Since the expected precision of the altimeter is ±10 cm, this means a geoid to this order—an extremely demanding task. The situation is as follows. From Figure 1, the altimeter gives us h; the position of the satellite provides H. The difference is $N+L$. Disregarding any error in h and H, it is still necessary to separate N from L, in order to provide the requisite reference surface. There are a number of possible approaches, none of which is really attractive. The most reliable and certain way to obtain surface gravity at sea is via shipboard gravimeters. But this at present appears impractical on a global scale. SEASAT-A data itself can be used by analyzing the altimetry, obtaining extremely accurate orbits, and attempting to filter the topographic "noise" in the altimetry. The periodic phenomena may be accounted for in this fashion by repetitive observations over the same areas. Another possibility is to attempt to obtain high-frequency gravitational data from other satellites, for example, a drag-free satellite or a low-altitude satellite tracked from a high-altitude one. However, the attenuation in a satellite of this nature at a minimum practical altitude of 300 km. is still very large. For example, based on Kaula's rule-of-thumb $10^{-5}/l^2$ for the magnitude of harmonic coefficients, the contribution to geoid height due to all harmonics of degree 60 is 20 cm. At 300 km height this is attenuated by a factor $\left(\frac{6.4}{6.7}\right)^{60} = .06$, so that the corresponding effect at 300 km height is about 1 cm perturbation

in the equipotential surface, or consequently that a 19 cm distortion in geoid height has been introduced which is larger than the precision of the altimeter. Thus it is difficult to see how any satellite-based systems of this nature can help the situation. A more interesting possibility is a low-flying satellite-borne gravity gradiometer which measures gravity directly rather than having it inferred from satellite perturbations. This still suffers from the fact that it is sampling an attenuated field but at least it bypasses the problem that the buildup of the perturbative force on the satellite is inversely proportional to the degree number of the spherical harmonic component of the potential.

Possible theoretical remedies involving the principle of downward continuation do not appear at present to offer much hope for resolution of the problem. Basically, the problem is akin to the geophysical inverse problem, and is at the same level of difficulty.

The solution thus is not at all clear at this point. Information will have to be taken from various sources. Even gravity at sea by itself is not sufficient, because Stokes' integral demands gravity everywhere, so that similar information must be available on land. Hopefully, by utilizing all possible information and employing iterative techniques, progress may be made toward a satisfactory determination of an adequate reference surface for the sea surface topography.

Let us now turn to some prospects of intrinsic value for geodesy itself. The inverse of Stokes' formula provides a direct means of computing gravity anomalies from geoid heights. In this case, geoid heights are the observables, and gravity anomalies the computed result. If geoid heights were available in sufficient quantity, accuracy, and distribution, it would then be possible to obtain gravity anomalies in selected ocean areas which might even serve as a basis for geophysical prospecting, as is done on land. However, there are two serious flaws in this rather shallow reasoning. The first is the problem carried over from the previous discussion that the so-called "geoid heights" which are observed are not really geoid heights but contain sea surface topographic noise, and the difficulty in filtering these out is quite substantial. The second is that there is not much background of experience in the utilization of the inverse Stokes' formula and questions may arise which cannot be anticipated on the basis of parallelism with Stokes' formula itself. For example, there is a built-in bias in the integral

$$\Delta g_i = -\frac{\gamma N_i}{R} - \frac{\gamma}{16\pi R^3} \iint \frac{N - N_i}{\sin^3(\psi/2)} \, d\sigma$$

which is not present in Stokes' formula

$$N_i = \frac{1}{4\pi\gamma R} \iint S(\psi)\,\Delta g \, d\sigma$$

The bias is due to the presence of N_i in the integrand which in general is non-zero; N_i is the geoid height at the point i where the gravity anomaly Δg_i is being evaluated. Thus the average of N-N_i over the entire earth is not zero in the same sense that the average of Δg in the Stokes' integral is. The inference here is that it is even more essential to have complete geoidal height data in order to obtain gravity anomalies than in the corresponding dual problem of obtaining geoid heights from gravity anomalies, if the inverse Stokes' formula is employed.

Despite these serious difficulties they are not insurmountable and this particular prospect presents an attractive challenge.

Another geodetic application for SEASAT-A and allied systems is in the direction of the leveling problem. There is a current hot controversy on the accuracy of the U.S. leveling network. A discussion of this can be found in the March 1974 EOS in the report of the fourth GEOP research conference. From oceanographic investigations, the sea level slope on both east and west coasts of the U.S. decreases to the north, these results being based on steric leveling, which is calculated from measurements of the density field of the oceans. On the other hand, this conflicts by

about 1 meter with results obtained by classical spirit leveling along the coasts. Resolution of this discrepancy is extremely important. If there are systematic errors in the U.S. leveling network, NOAA definitely would like to know about it. It follows that precise information on the shape of the geoid and sea surface topography along the coasts could serve as a check and perhaps help resolve this controversy. Since the current discrepancy is of the order of a meter, the intrinsic difficulty in separating sea surface topographic components from the geoid is not quite as crucial here, and a very crude separation may yield some fruitful results.

Obtaining gravity anomalies from altimetry, as mentioned before, involves many complications. A related application, which is much more straightforward is the acquisition of deflections of the vertical at sea. This is the direct slope of the geoid, and thus can be obtained differentially. A global formula like Stokes' inverse theorem is not required. But a precise geoid still is. For example, if an accuracy of 1 second of arc were required for a deflection over 10 km horizontal distance, the geoidal height would have to be known to 5 cm. These deflections would have many useful applications, for example in checking the absolute orientation and positioning of the new North American Datum. However, the figures just mentioned indicate the magnitude of the task of obtaining the requisite accuracy.

The global geoid itself will be vastly improved by the altimetry data. This is straightforward. Serious issues do not arise until we begin to tackle the question of separating the sea surface topography from the geoidal undulations. Down to the one meter scale on a global basis the main problems are those of obtaining and handling sufficiently dense and well-distributed data. Of course a better geoid implies a better gravitational field which in turn means that other satellites can be more accurately tracked, in particular satellites employed for geodetic purposes. Such satellites can then be more effectively employed for station determination and absolute positioning.

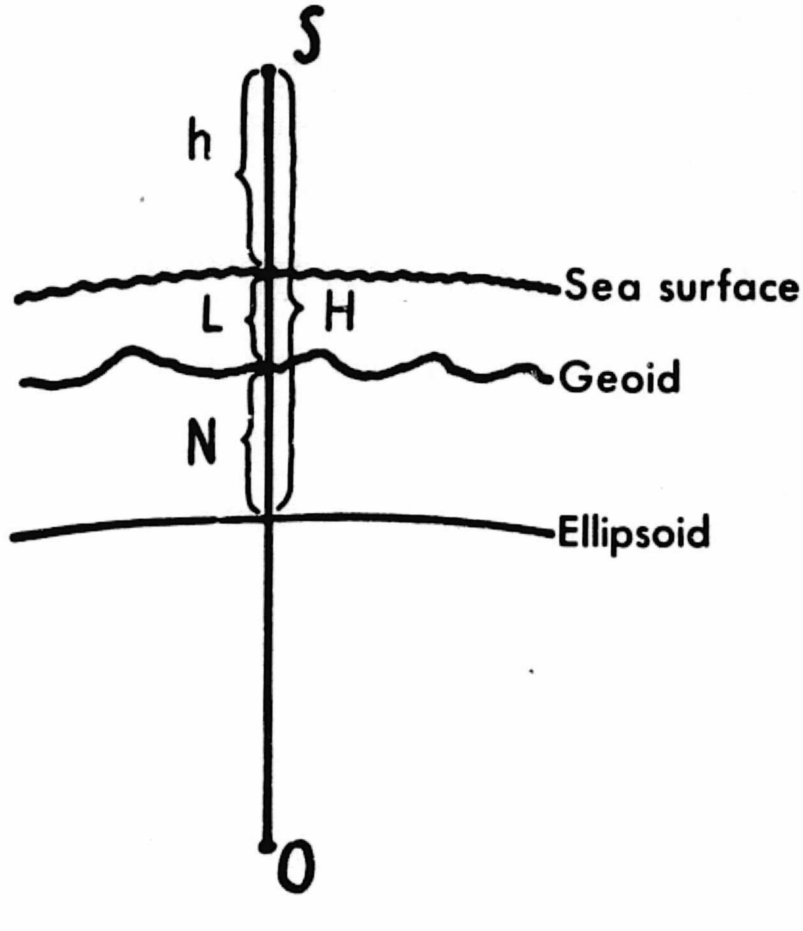


Figure 1.

N76 11491

OCEAN TIDES FROM SEASAT-A

M. C. Hendershott, W. H. Munk, and B. D. Zetler
Institute of Geophysics and Planetary Physics,
Scripps Institution of Oceanography, UCSD
La Jolla, California

Although efforts to chart global ocean tides achieved some limited success in the previous century, it has long been obvious that most of the tide stations were in the worst possible places, along the continents and even inside estuaries. In the last decade, accurate tidal measurements in the deep ocean have been taken. (These early developments and the geophysical benefits to be derived from a deep ocean tide program were described by *Munk and Zetler*, 1967.)

The state-of-the-art has improved to the extent that various organizations now have the capability to reliably measure tides on the sea floor at depths exceeding 5 km; in 1973 the IAPSO-SCOR-UNESCO Working Group No. 27, Tides in the Open Sea, organized an intercalibration exercise for tide gauges off the coast of France. Nevertheless, the logistics and expense of obtaining a global grid of ocean tide observations preclude such an operation; therefore oceanographers view with great interest the development of spacecraft altimetry as a means of obtaining global tide data.

When proposals were invited for participation in GEOS-C, the information provided indicated instrument altitude errors of ±2 meters for global altimetry and ±0.5 meter for localized altimetry. In a research proposal for this program in January 1973, we indicated some hope of success in localized studies but said the indicated accuracy for global studies was inadequate. We are glad to note a modification of the GEOS-C measurement objectives to 1 meter and 1/3 meter for local and global regions respectively and, even more, comparable objectives of 1/3 meter and 0.1 meter for SEASAT-A. This improvement in the state-of-the-art significantly improves the prospects of depicting global tides from spacecraft altimetry. However, it should be noted that each sea level observation depends just as much on accuracy of spacecraft positioning as on altimetry accuracy. Inasmuch as a tidal solution combines data obtained in various transits, accuracy in both positioning and altimetry is essential. Even if the derived tidal solutions are not per se acceptable, some degree of tidal correction may be possible that would meaningfully improve the delineation of sea surface topography as compared with a solution in which tides are treated as random noise.

Assuming the shape of a received altimetry signal can be interpreted for sea state, the observed sea level value includes: (1) a constant anomaly from the geoid due to local gravity fields; (2) a variable geostrophic anomaly with a pronounced seasonal component; (3) a periodic sea floor variation (earth tide); (4) an ocean tide; (5) meteorological contributions (pressure and wind); and (6) noise. A satisfactory investigation of ocean tides must give consideration to all of these.

We envision two procedures for the eventual evaluation of global tides; an *empirical method* leading to the response functions for a grid of about 500 points (about 1000 km apart) from which, by suitable interpolation, the tide can be predicted for any point in the oceans. This is essentially an expansion of the response method of tide operation. Secondly, a *dynamic method* which consists of iteratively modifying the parameters in the numerical solution to the Laplace tide equations.

With the GEOS-C data, the initial concentration of the effort will be in the GEOS-C Calibration Configuration (Wallops Island, Cape Kennedy, Antigua, Bermuda) to take advantage of the greater accuracy achieved by localized altimetry (Mode II). The 1973 MODE experiment falls within this area and has achieved a determination of major tidal constants to better than 1 mm (*Zetler et al.*, 1974); therefore it will be possible to use the MODE data as "sea truth" for the tidal regime. For other areas, a less than satisfactory projection of coastal tide data must be used.

EMPIRICAL METHOD

An empirical method (*Munk and Cartwright*, 1966) is used to best fit observed heights (in the least square sense) to input functions which are the time-variable spherical harmonics of the gravitational potential and of radiant flux on the Earth's surface. From the weights that are determined by these procedures, frequency-dependent admittances are derived that describe the tidal characteristics in a sense similar to what can be deduced from traditional harmonic constants.

An interpolation scheme would be used with the observed data to provide values at nearby grid points. The derived weights can be used with gravitational and radiational predictions to obtain predictions for each of the grid points. Prediction for other locations in the oceans can then be obtained by interpolation procedures.

The formalism can be outlined as follows. Let $c_2^m(t)$ be the known amplitudes of the spherical tidal harmonics. Then for any grid point j the predicted tide is

$$\eta_i(t) = \sum_{m=0}^{2} \sum_{\tau} w_{j,m}(\tau)\ c_2^m(t-\tau)$$

where w is the weight in the least-squares sense. Any observed tidal departure can be compared to interpolated values from neighboring grid points:

$$\zeta(t) = \sum_j r_j n_j(t)$$

where r_j are the appropriate interpolation coefficients. The w's are evaluated by a matrix inversion using $\zeta(t)$ from the satellite observations.

DYNAMIC METHOD

The dynamics method attempts to solve the Laplace tidal equations, using a topographic grid of the oceans and specifying some conditions, such as vanishing normal velocities at coastlines and specified (observed) values at coastal stations and/or at selected islands. They may include dissipation of energy and the effects of solid earth tides. We propose to apply these procedures to an input of observed elevations at a network of stations obtained from an altimeter, initially for the local area with maximum accuracy and eventually on a global scale.

DATA

We assume that the shape of the received altimetry signal can be interpreted for sea state and that orbit calculations will be available so that absolute sea level values can be obtained. Inasmuch as we propose to calculate tides at a relatively small set of points (about 500, 1000 km apart for a global solution), an interpolating system will be developed to interpolate from the observed paths to the nearby points. The spacing of points is not critical and certainly there will be more than we will want to use, so some lowpassing and decimation will be programmed. Neither method poses a requirement for revisit of a specific location. Available bottom pressure measurements, obtained simultaneously with altimetry data, will be used for "sea truth" comparisons, bearing in mind variations due to earth tides and barometric fluctuations.

Although the SEASAT-A measurement objective of 0.1 meter is still two orders of magnitude more coarse than the state-of-the-art in bottom pressure measurement (1 millimeter), nevertheless there is reason to hope that other advantages of the altimetry program (spacial coverage, frequent sampling, and long duration of observations) will offset the accuracy deficiency. Ultimately there are a host of applications to a "solution" of the global tide problem, among them a better calculation of the dissipation of tidal energy in the world's oceans, and information concerning the plastic properties of the solid Earth. The fluctuating tidal currents flowing in Earth's magnetic field generate electric potentials that can be measured with suitable electrodes on the sea bottom. The generated potential depends also on the conductivity within the Earth; with the tides known, the effective conductivity can be estimated for various tidal frequencies (and hence effective depth). These estimates in turn give information about the distribution of temperature in Earth's upper mantle. Horizontal temperature gradients within Earth, particularly beneath the ocean boundaries, are associated with a stress field that may be responsible for the principal belts of volcanic and seismic activity. In fact, all variable geophysical processes on the planet Earth at tidal frequencies are affected by ocean tides; not until these can be adequately corrected for ocean tides can we expect to take full advantage of the measurements.

Quite aside from tidal corrections to land measurements, one of the most important potential contributions is a determination of sea level with tides and waves properly removed. This slowly varying topography is intimately connected to shallow ocean circulation, which in turn has important bearing on problems of weather and biological productivity.

REFERENCES

Munk, W. H., and D. E. Cartwright (1966), Tidal spectroscopy and prediction. *Phil. Trans. Roy. Soc. London, A*, 259, 533-581.

Munk, W. H., and B. D. Zetler (1967), Deep-sea tides: a program. *Science 158*, 884-886.

Zetler, B. D., W. H. Munk, H. Mofjeld, W. S. Brown, and F. O. Dormer (1974), MODE tides, *J. Phys. Oceanogr.* (in preparation).

N76 11492

EXPECTED SEASAT-A SCIENTIFIC RESULTS

Frank E. Hoge
NASA Wallops Flight Center

OCEAN GEOID

Over those parts of the ocean covered by SEASAT-A a highly refined geoid determination is expected. Many new features were observed with the SKYLAB altimeter but the higher accuracy and extended coverage of the SEASAT instrument will allow more accurate surface topography at more frequent intervals for higher correlation of results. A higher spatial frequency geoid is also expected on the basis of recent analysis of SKYLAB data in the Equatorial Mid-Ocean Canyon region of the North and South Atlantic Oceans. The higher frequency geoid capability of altimeter data is adequately displayed in the Puerto Rican Trench Pass 4 and Pass 6 data from SKYLAB's SL-2 mission (*McGoogan et al.*, 1974) compared to the Marsh-Vincent geoid (Figures 1 and 2). The frequency content of radar altimeter data is limited to wavelengths longer than the order of a kilometer by the footprint of the altimeter as shown in Figure 3.

The two virtually coincident SKYLAB passes over the Puerto Rican Trench anomaly which had been indicated in other data verified its existence. The data were limited to the southeastern corner of the trench and island in an area which had not been extensively mapped. Numerous additional transects over this particular area with the more precise coverage of SEASAT-A will allow not only the broad features of the trench to be mapped but more subtle high frequency ones also. In addition it is anticipated that new features will be discovered and ocean surface topography which is not as well known can be studied in detail.

OCEAN CURRENTS

The high resolution pulse compression radar altimeter on SEASAT-A will be used in several ways to attack the problem of open ocean currents and circulations. (a) Clearly the most obvious and direct approach to the measurement of currents is to observe their geostrophic nature by direct profiling with the radar altimeter. The 10 cm precision of the SEASAT-A altimeter is about ten times smaller than select peak-to-trough topography variations in the Gulf Stream in the mid-North Atlantic due East of the United States. This renders the mapping of this particular current possible. (b) Detection of ocean currents is expected on SEASAT-A by observing the changing statistical distribution of the radar altimeter return video leading edge rise time as the satellite traverses a wave-current boundary, passes through the current itself, and then proceeds across the other wave-current boundary. (c) On a theoretical basis, *Huang et al.* (1972) found that the rms surface slope of ocean waves is sensitive to a change in current conditions caused by a wave-current interaction. The pulse amplitude changes of the radar altimeter will also be useful in detecting ocean currents. For example, the number of specular returns received during the satellite traversal of a current is expected to be larger than over non-current areas. Thus the statistical pulse height distribution would change when currents are encountered. Theoretical investigations are proceeding to place these techniques on a firm basis. The use of SKYLAB radar altimeter data to support these investigations is underway and further refinements of the models and experi-

ments are projected using GEOS-C data. Of course, experience must be acquired in calibration over known currents such as the Gulf Stream and knowledge of the variance of the pulse height distribution over differing sea conditions (Figure 4).

OCEAN SUBSURFACE TOPOGRAPHY

The scientific community generally agrees that satellite altimeters measure ocean surface topography variations or undulations. These undulations are principally composed of (a) static geoid highs (and lows) caused by gravity variations in the earth crust and upper mantle, (b) surface topography highs (and lows) caused by currents and open ocean tides, and (c) other spacially more random effects such as pileup, atmospheric pressure effects, etc. These dominant effects are combined in an unknown mixture believed to be more predominantly gravity. The contribution due to currents is expected to be largely accounted for by the techniques discussed above.

The spacially more stable gravity induced portions of the ocean surface topography must be understood first (bias effects caused by sea state in discrete areas are assumed to be negligible). Ocean current maps and geoid maps having the necessary high resolution useful for comparison with satellite altimeter data simply do not exist. In lieu of these maps the next best source o. collected data is ocean bottom topography. In some cases the degree of correlation of altimeter data and bottom topography is very high. In these specific instances then the geoid shape can be accurately replaced by low-pass-filtered bottom topography information. Should adjacent satellite tracks over a large area show high correlation with bottom topography then the geoid shape in that entire area would be represented by the bottom topography. In short, satellite altimetry data will be useful in generating high spacial resolution geoid maps by defining those areas where the geoid can be truly represented by filtered bottom topography data. This entire procedure is analogous to the technique used by *Talwani et al.*, 1972, to interpolate gravity values between observation points on the basis of bottom topography.

In those cases where a high degree of correlation does not exist between the altimetry data and the bottom topography, then additional information must be sought to evaluate the altimeter and generate good geoid maps. For example, accurate subbottom geological structure sections (and/or models) extending down to the top of the mantle can be gravimetrically projected to show the effect on the geoid. Conversely, where ocean currents, sea state, pile-up, and tides are well determined, then the gravity contribution to ocean surface topography or geoid will be uniquely known.

With a precision 10 times better than the SKYLAB altimeter, the SEASAT instrument will be capable of far more sensitive determination of sea surface topography. The best demonstrated sensitivity of the SKYLAB altimeter to date is the observation of topographic and geological effects of a known seamount off the coast of South America shown in Figure 5 (*Leitao and McGoogan*, 1974). The base of the seamount is about -4 km below the surface while the top of the seamount rises to within about 500 meters of the surface. The radar altimeter data show an ocean surface height or convex topography feature of about 8 meters. A seamount in the vicinity of the Cape Verde Islands has also been detected (*McGoogan, Leitao, and Wells*, 1974). This seamount and correlation with the Marsh-Vincent geoid is shown in Figure 6.

The high resolution SEASAT-A data will allow verification of the models being developed to describe the correlation between the ocean surface topographical variations and subsurface features such as seamounts, escarpments, and plateaus. The superior sensitivity of the SEASAT-A altimeter will allow correspondingly deeper seamounts and features

to be located. The study of seamounts, ridges, escarpments, trenches, and caps is important to the understanding of crustal modeling, tectonic plate motion, and the interaction of the lithosphere with the asthenosphere, and the role of hot spots, etc.

EARTH SURFACE TOPOGRAPHY

The SEASAT-A mission, as implied by the satellite and program names, will be configured to make major advances in ocean science and applications. Furthermore the radar altimeter hardware will be designed specifically to operate over the oceans–not the land areas. However, there is sufficient experimental data from the SKYLAB S-193 radar altimeter mission to indicate that the SEASAT-A altimeter should be operable over land areas as well. The SKYLAB altimeter operated unexpectedly well over land areas of Venezuela (*McGoogan et al.*, 1974); see Figures 7 and 8. SKYLAB radar altimeter data has also shown good correlation with known contour map data in the vicinity of the Chesapeake Bay in Maryland and the Sacramento Valley area of California. See Figures 9 and 10 (*Plugge*, 1974). No doubt some of the land areas profiled by the SKYLAB altimeter have never been traversed by geodetic survey teams.

ORBIT REFINEMENT USING THE RADAR ALTIMETER

The radar altimeter on SEASAT-A is looked upon primarily as a system for studying sea state, ocean surface topography, surface winds, etc. In this mode the altimeter spacecraft is tracked by ground stations to yield a good orbit against which the altimeter data can be compared. It is also important that the radar altimeter be looked upon as a tracking station in orbit ranging to the earth as the target. Experience with the SKYLAB S-193 altimeter has demonstrated the high stability of the instrument and data. Work is now in progress to demonstrate the orbit refinement capability of radar altimeter data and the possibility of self-calibration.

REFERENCES

Huang, N. E., D. T. Chen, and Chi-Chao Tung, "Interactions between Steady Non-uniform Currents and Gravity Waves with Applications for Current Measurements," Jour. Phy. Ocean. *2*, 420 (1972).

Leitao, C. D., and J. T. McGoogan, "SKYLAB Radar Altimeter: Ocean Surface and Ocean Bottom Topography Correlation," Submitted for publication in Science.

McGoogan, J. T., C. D. Leitao, and W. T. Wells, "SKYLAB Altimeter Applications," Paper to be presented to Union of Radio Science International (URSI), Microwave Scattering and Emission Meeting, September 23-26, 1974.

McGoogan, J. T., L. S. Miller, G. S. Brown, and G. S. Hayne, "The S-193 Radar Altimeter Experiment," Proc. IEEE *62*, 793 (1974).

Plugge, R. J., Editor, "SKYLAB Sensor Performance Evaluation Report Vol. V (S-193 Altimeter)," Document # MSC-05529 under Contract #NAS8-24000 (JSC - 14S), Feb. 1974.

Talwani, M., H. R. Doppe, and P. D. Rabinowitz, "Gravimetrically Determined Geoid in the Western North Atlantic," in Sea Surface Topography from Space, Volume 2, NOAA Technical Report ERL-228-AIML 7-2, Ed. by John R. Apel, Boulder, Colorado, 1972.

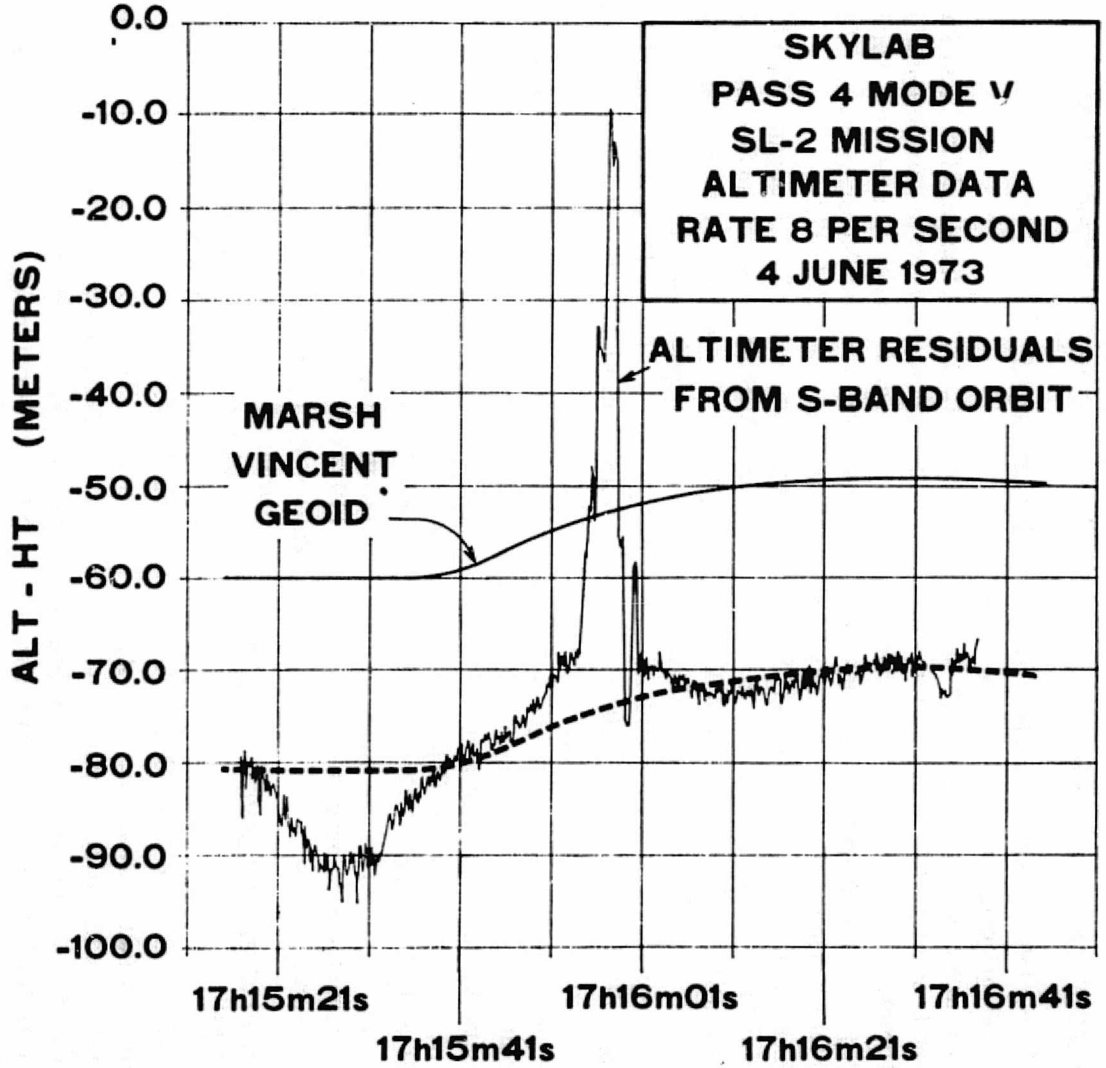

SKYLAB
PASS 4 MODE V
SL-2 MISSION
ALTIMETER DATA
RATE 8 PER SECOND
4 JUNE 1973
ALTIMETER RESIDUALS
FROM S-BAND ORBIT
MARSH
VINCENT
GEOID
ALT - HT (METERS)
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
17h15m21s
17h15m41s
17h16m01s
17h16m21s
17h16m41s

Figure 1.

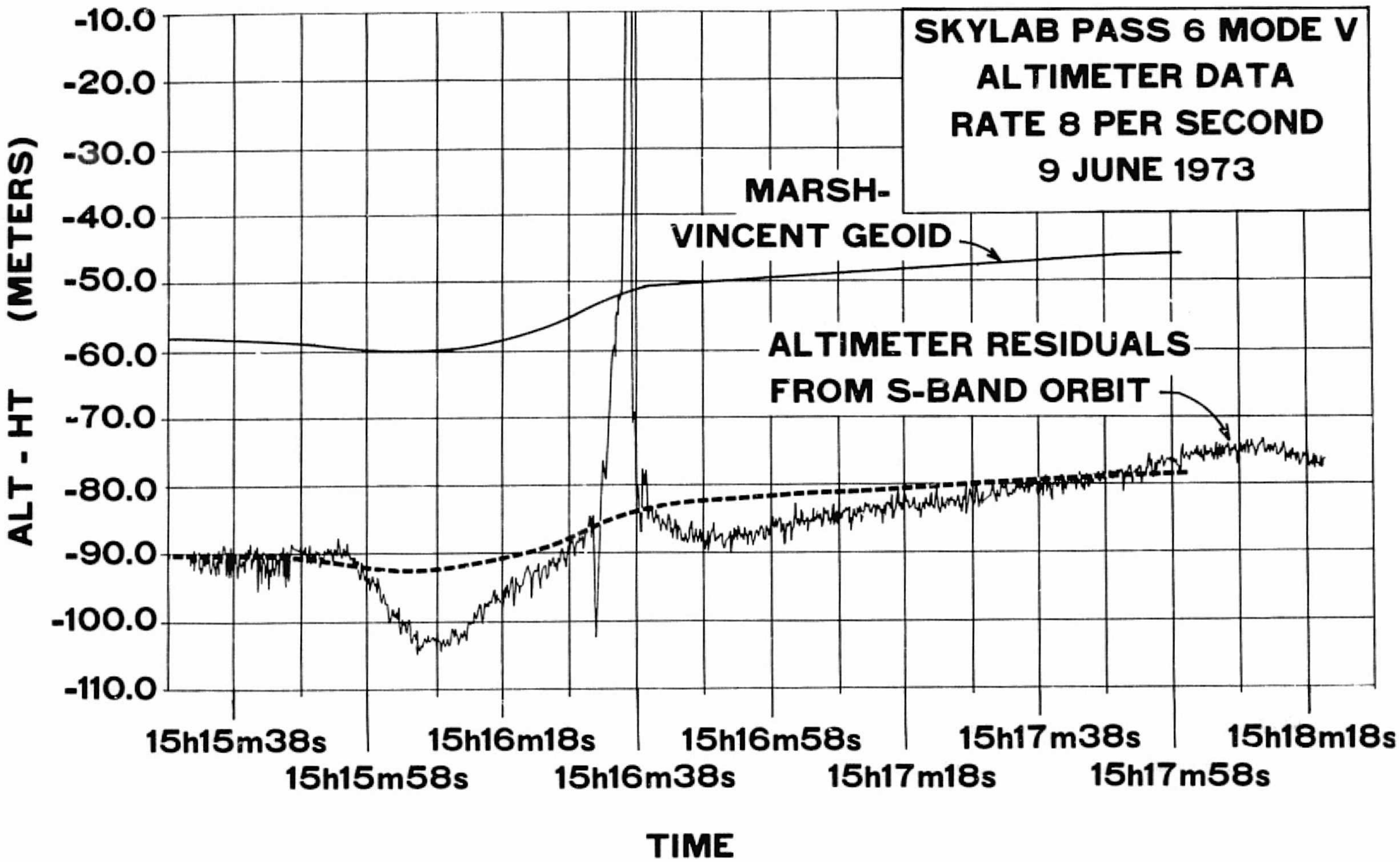


Figure 2.– Comparison of altimeter residuals from orbit with Marsh-Vincent geoid in the vicinity of the Puerto Rican Trench. Pass #6.

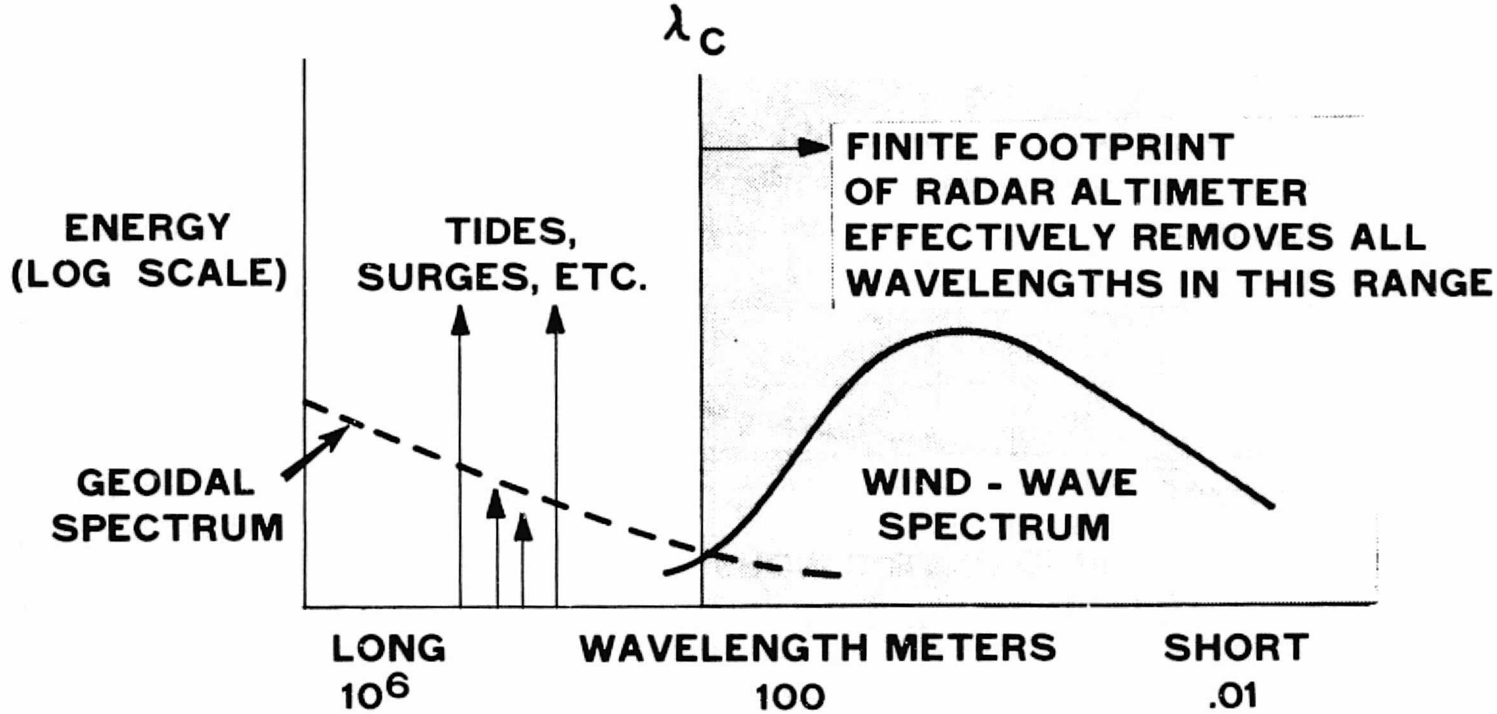

λc
FINITE FOOTPRINT
OF RADAR ALTIMETER
EFFECTIVELY REMOVES ALL
WAVELENGTHS IN THIS RANGE
ENERGY
(LOG SCALE)
TIDES,
SURGES, ETC.
GEOIDAL
SPECTRUM
WIND - WAVE
SPECTRUM
LONG
10^6
WAVELENGTH METERS
100
SHORT
.01

Figure 3.

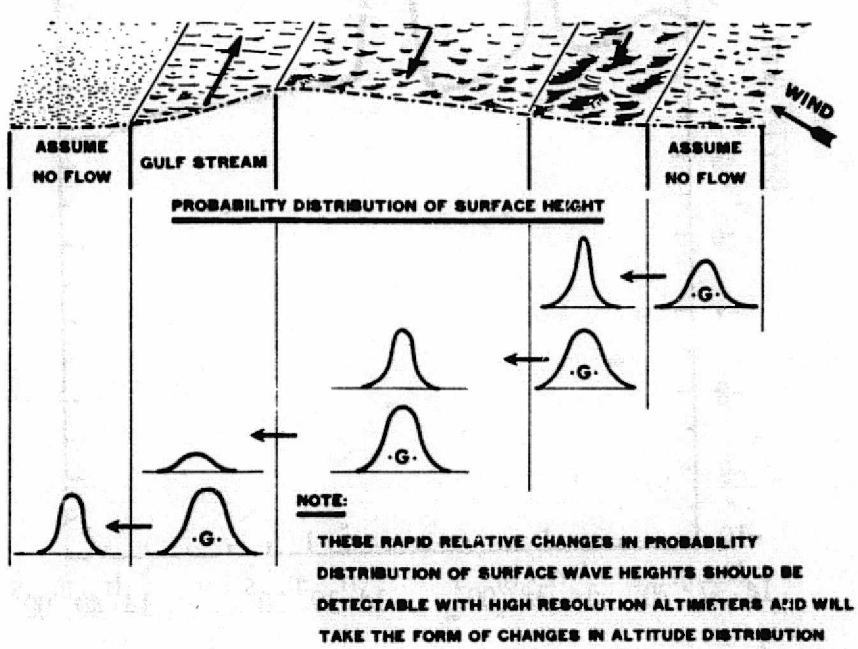


Figure 4.–Detection of Gulf Stream with altimetry.

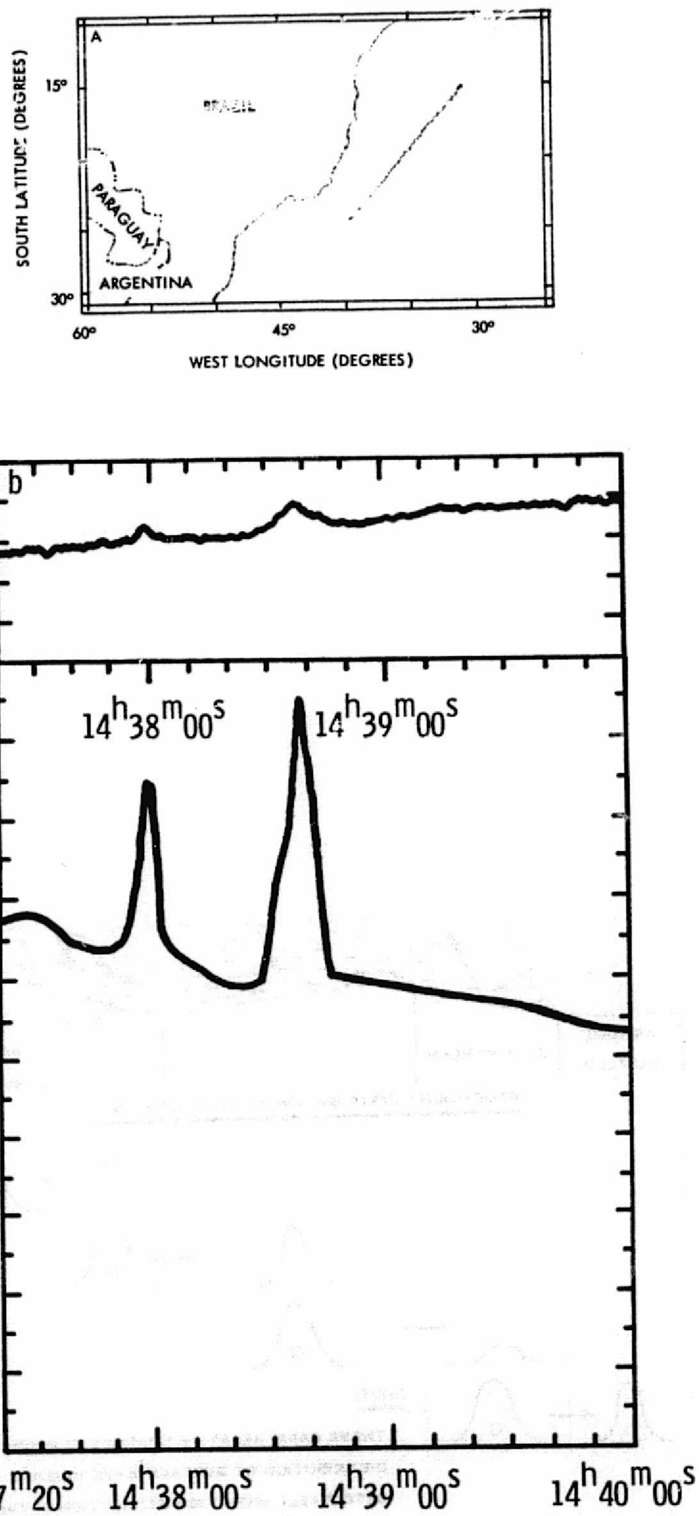
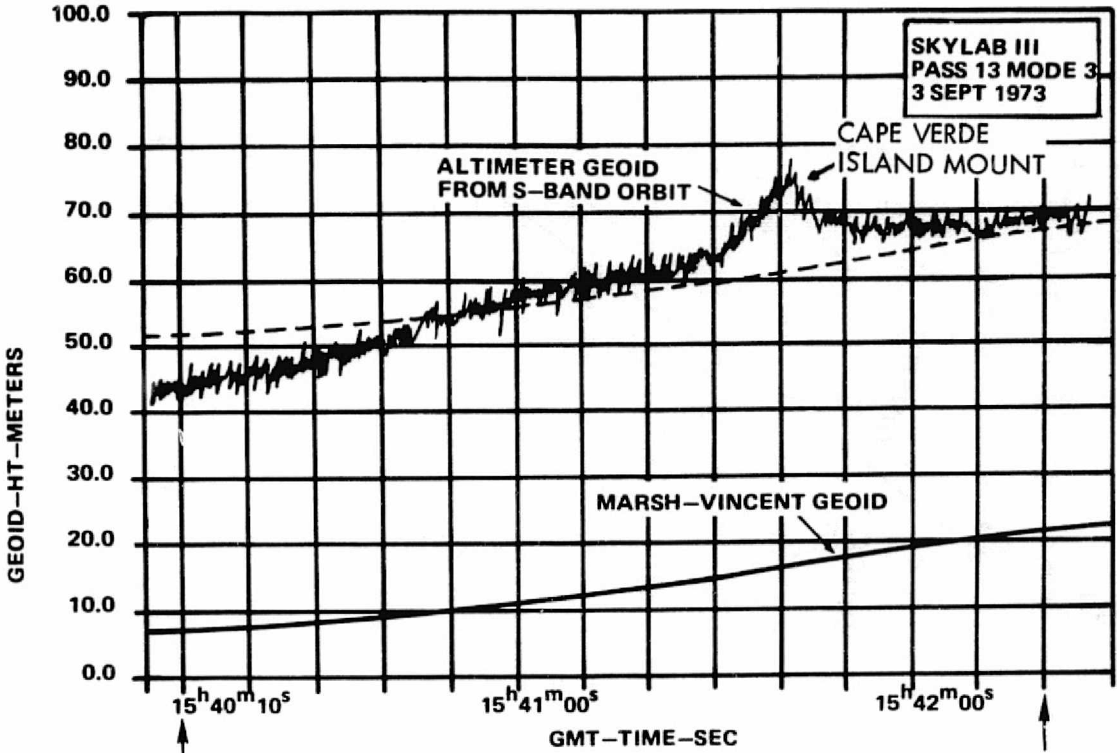

A
SOUTH LATITUDE (DEGREES)
15°
30°
PARAGUAY
ARGENTINA
60°
45°
30°
WEST LONGITUDE (DEGREES)
b
RESIDUALS (m)
0
-10
-20
-30
-40
-50
DEPTH (km)
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
14h38m00s
14h39m00s
14h37m20s
14h38m00s
14h39m00s
14h40m00s

Figure 5.


SKYLAB III
PASS 13 MODE 3
3 SEPT 1973
CAPE VERDE
ISLAND MOUNT
ALTIMETER GEOID
FROM S-BAND ORBIT
MARSH–VINCENT GEOID
GEOID–HT–METERS
GMT–TIME–SEC
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
15h40m10s
15h41m00s
15h42m00s

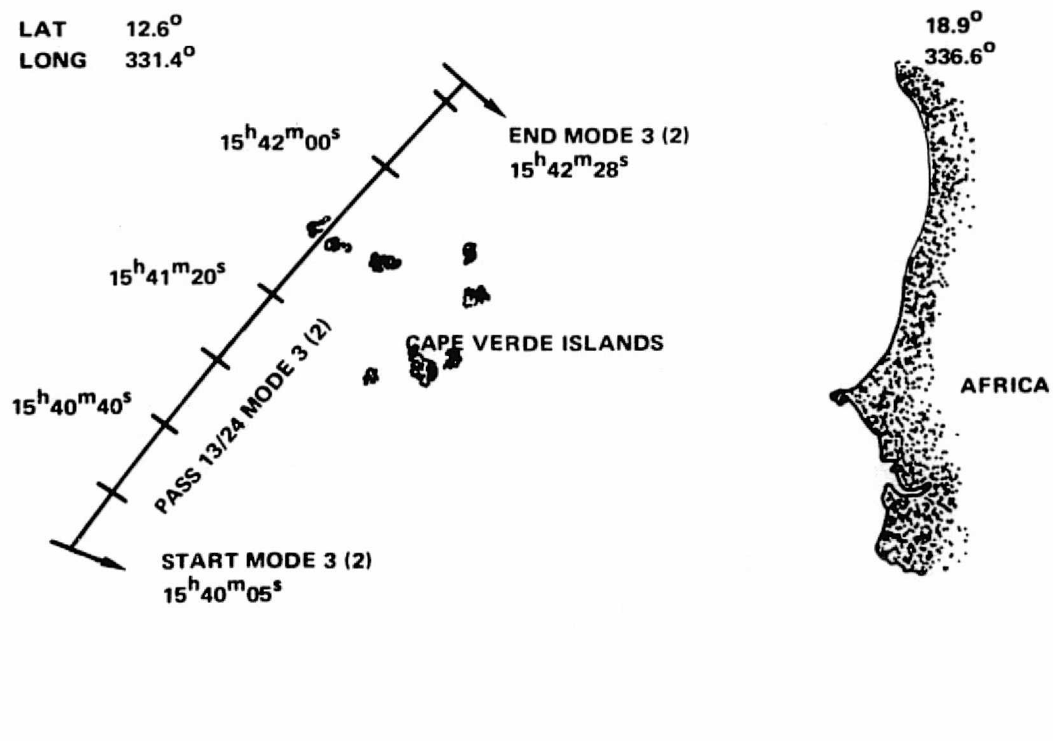

LAT 12.6°
LONG 331.4°
18.9°
336.6°
15h42m00s
END MODE 3 (2)
15h42m28s
15h41m20s
15h40m40s
PASS 13/24 MODE 3 (2)
CAPE VERDE ISLANDS
AFRICA
START MODE 3 (2)
15h40m05s

Figure 6.

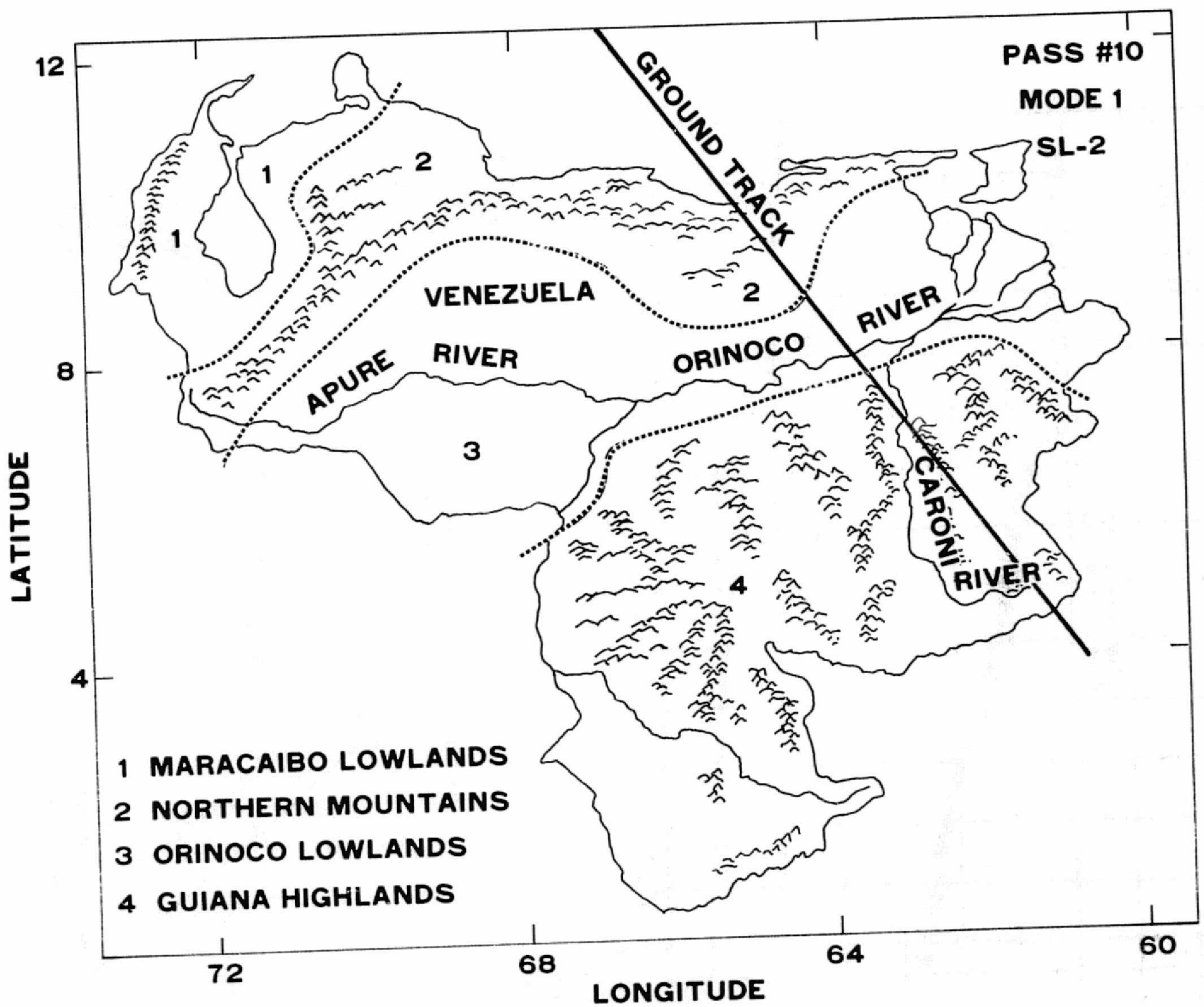

PASS #10
MODE 1
SL-2
GROUND TRACK
VENEZUELA
APURE
RIVER
ORINOCO
RIVER
CARONI
RIVER
1
1
2
2
3
4
12
8
4
LATITUDE
72
68
64
60
LONGITUDE
1 MARACAIBO LOWLANDS
2 NORTHERN MOUNTAINS
3 ORINOCO LOWLANDS
4 GUIANA HIGHLANDS

Figure 7.

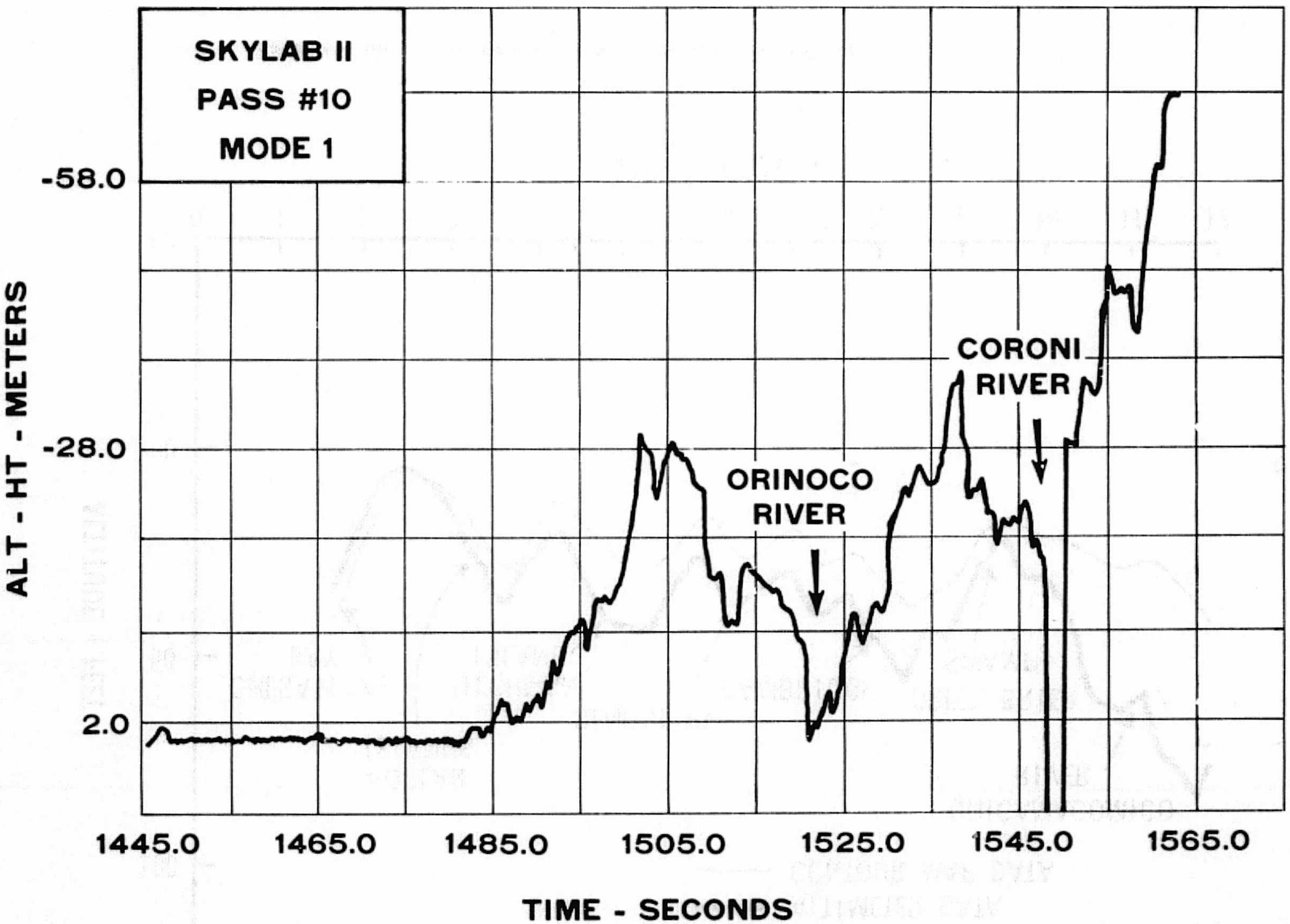

SKYLAB II
PASS #10
MODE 1
ALT - HT - METERS
-58.0
-28.0
2.0
ORINOCO RIVER
CORONI RIVER
1445.0
1465.0
1485.0
1505.0
1525.0
1545.0
1565.0
TIME - SECONDS

Figure 8.

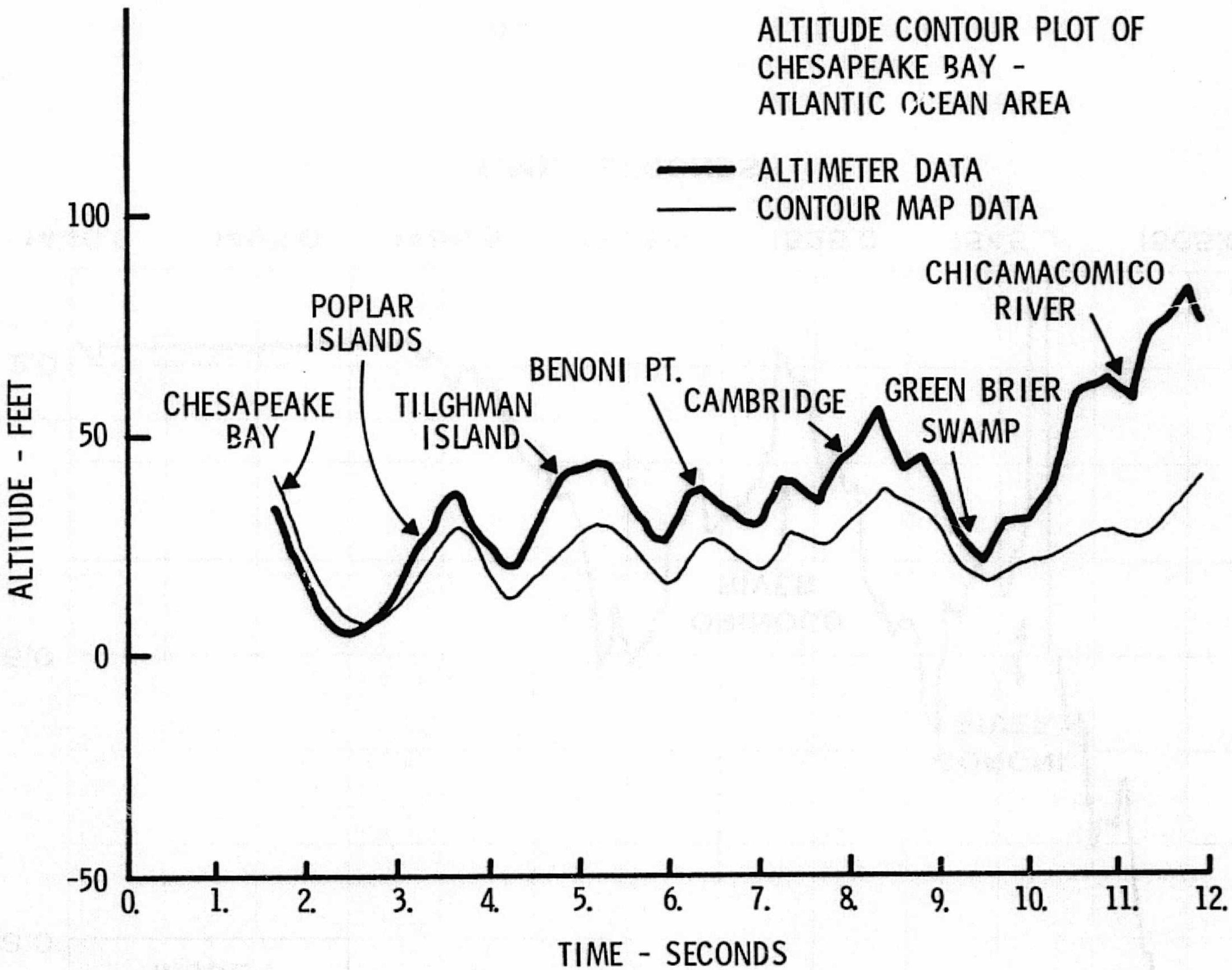


Figure 9.– Altitude contour plot of Chesapeake Bay, Atlantic Ocean area.

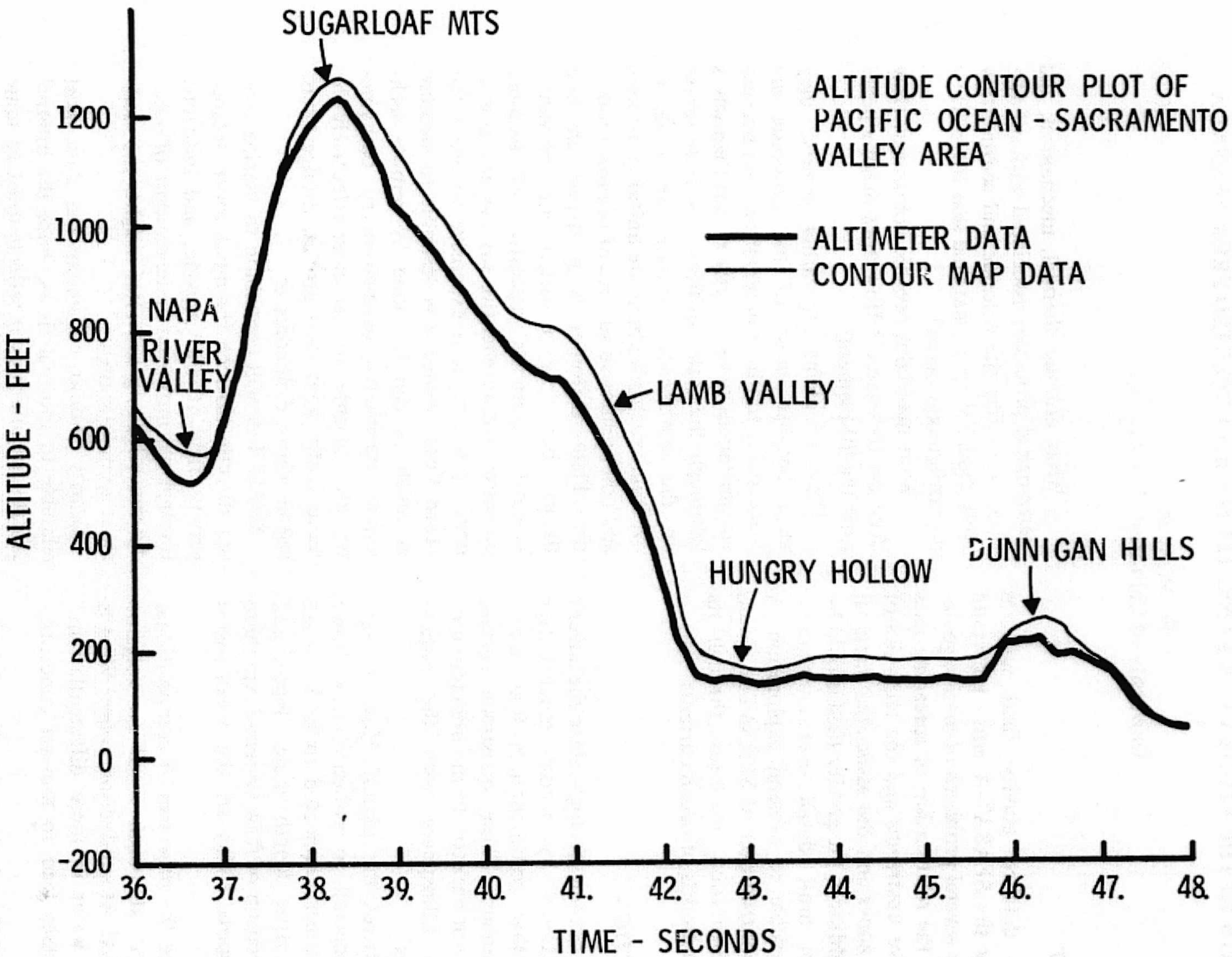


Figure 10.– Altitude contour plot of Pacific Ocean, Sacramento Valley area.

N76 11493

BENEFITS TO THE STUDY OF OCEANIC TECTONICS EXPECTED FROM SEASAT-A

W. M. Kaula
University of California, Los Angeles

ABSTRACT

A more detailed gravity field such as provided by the SEASAT-A altimeter would help resolve several problems of marine geology, such as the relationship of spreading rises to convective upstreams and the tectonics of subduction zones and the associated marginal basins. In addition, the gravity field should be measured in more detail over continental shelves accessible to mineral exploration. A secondary contribution of SEASAT-A would be to sedimentation processes, through its influence on models of ocean currents.

INTRODUCTION

Although oceanic geology, since the advent of plate tectonics, has become much better understood than continental geology, many questions remain. These questions pertain mainly, but not entirely, to the interaction of the oceanic lithosphere with the asthenosphere below.

What drives the plates? How is plate motion connected to asthenospheric flow? How is volcanism connected to it? What are the characteristic length scale, depth, and temporal variation of flow systems? Are there fixed "hot spots"? Why are the ocean basins so deep?

What are the processes of compositional differentiation at ocean rises? At volcanic accumulations? At subduction zones? What is the role of water in these differentiations? Which processes lead to mineral concentrations?

What are the relative roles of continental proximity, biologic activity, and ocean current dynamics in sedimentation? What controls petroleum-bearing concentrations?

What are the thermal, mechanical, and petrological processes associated with subduction zones and the volcanic and sedimentary belts above? Why do marginal seas form? How do earthquakes occur?

What maintains oceanic volcanism? How deep are its sources? How does magma penetrate the lithosphere?

These problems are rather general; they exist because most of the processes are inaccessible to direct observation, and because circumstances never exactly repeat themselves (although the latter difficulty is more severe on the continents). Among the needs to overcome such situations are unifying theories and comprehensive surveys of oceanic properties. Plate tectonics is a strong unifying theory, but only a partial one, providing kinematic contexts suggestive of tectonic processes. Comprehensive surveys are an economic problem; it is expensive to probe the ocean floor. Hence it is desirable to measure as much as can be done by remote techniques–gravimetry, magnetometry, bathymetry, etc.–in order to plan more effectively the more costly heat flow probes, dredge hauls, seismic shots, drill cores, etc.

SEASAT-A will contribute to marine geology directly through the much more detailed gravity field it will provide, and indirectly through the improved understanding of ocean dynamics leading to better insights into sediment accumulation.

Gravity should be among the data most relatable to internal flows, since the internal density irregularities it reflects must to some extent drive or be sustained by such flows. Correlations of the gravity field with the plate tectonic pattern have been evident for about five years (*Kaula*, 1972a, b). However, these

correlations have been rather loose on a global scale, and hypotheses as to cause and effect relationships to tectonic processes have been rather speculative. This looseness is in part due to the resolution of the gravity fields available being no better than 1500 km for much of the world. In regions where more detailed data are available, it has been possible to construct more specific and meaningful hypotheses, as described below.

A more detailed gravity field globally such as the SEASAT-A altimeter could provide—20 cm geoid height change is typical of the geoid height change in 10 km—would be a valuable reconnaissance tool to help decide where to undertake shipborne surveys, as well as directly providing constraints to tectonic models. We discuss herewith several examples of such constraints, taking the different oceanic geological provinces in the usual sequence from youngest to oldest.

OCEAN RISE CRESTS

The correlation of satellite-determined gravity anomalies with spreading boundaries of the plate tectonic system is positive in a rather spotty way (*Kaula*, 1972a, b; *Lambeck*, 1972; *Anderson et al.*, 1973): some places it is strongly positive, particularly along the slower spreading North Atlantic and Southwest Indian Ocean rises; more places it is mildly positive; in some it is actually negative, such as the southernmost portion of the Pacific rise. Perhaps this correlation should be spotty, since most rises are moving at rates of a cm/yr or more with respect to any plausible mantle-fixed reference frame (*Minster et al.*, 1974), and at times in the geologic past have jumped a few hundred kilometers (*Sclater et al.*, 1971). In any case, for shorter wavelengths on the order of 100 km there is a marked positive correlation of rise topography with gravity where shipborne gravimetry is available (*Lambeck*, 1972). Detailed gravimetry over a band 1000-2000 km wide along several 1000 km of ocean rise would furnish excellent guides as to where heat flow and detailed bathymetry should be measured, and improve our understanding of the degree to which the necessarily passive spreading boundaries are related to the locations of convective upstreams. It would also indicate more strongly whether the convective upstreams are more circular or arcuate in horizontal planform.

OCEAN RISE FLANKS AND VOLCANISM

Volcanoes appear to be often born on rises, but to experience much of their growth when already several hundred kilometers off the rise (*Menard*, 1969). The correlation of volcanism with gravity anomalies is much more consistent than that of ocean rises (*Kaula*, 1972a, b; *Morgan*, 1972), as though both have a common cause in the excess pressure created by some convective upcurrent. In addition, there appear to be positive correlations of sea floor bumps not known to be volcanic with gravity, suggesting another convective effect (*Menard*, 1973). However, again this is a speculation dimly perceived in the data; more detail would greatly clarify the matter.

ABYSSAL PLAINS

The most systematic relation between the gravity field and topography is that negative anomalies prevail over the great ocean basins (*Kaula*, 1972a, b). Recent inferences of lithospheric thickness increases from Rayleigh waves in such regions (*Leeds*, 1973) tend to confirm the hypothesis that the occurrence of these negatives is due to acceleration (in the Lagrangian sense) of asthenospheric material by being dragged along by the lithosphere (*Kaula*, 1972b). However, significant convective downcurrents under the ocean basins cannot be ruled out. It is not clear how more detailed gravimetry would help resolve the questions, but we really do not know.

CONTINENTAL SHELVES AND SLOPES AND SEDIMENTATION

The continental shelves and slopes occurring at Atlantic type ocean margins are comparatively quiet tectonically, and hence not generally marked by broad gravity anomalies. However, they are regions of comparative accessibility and hence of mineral potential, which warrants more detailed gravimetry. The petroleum possibilities of the U.S. Atlantic shelf and slope are very poorly known, for example.

Because of their proximity to the continents, these regions are marked by heavy sedimentation. These sediments are carried down the slope to the abyssal plains primarily, it is thought, by turbidity currents: downslope flows of sediment laden water. However, the size distribution and geographic location of sediments are also significantly influenced by ocean currents (*Schneider*, 1972; *Watkins and Kenneth*, 1973; *Heezen and MacGregor*, 1973; *Jones et al.*, 1970), so sedimentation is a subject area where SEASAT-A may have influence on marine geology through its influence on modeling of ocean dynamics, a subject which applies to the past as well as the present (see, e.g., *Gill*, 1971).

SUBDUCTION ZONES, ISLAND ARCS, AND MARGINAL BASINS

It has generally been thought that the pronounced positive anomalies behind trench and island arcs were due to the subducted slab (*Kaula*, 1972a, b; *Griggs*, 1972). However, this appears to be an oversimplification. Positive anomalies seaward of the trench appear to arise from compressive upbuckling of the lithosphere before it descends (*Watts and Talwani*, 1974). It also is a puzzle as to why positive gravity anomalies should exist over all the marginal basins behind the western Pacific island arcs. These complex basins are the result of secondary tectonic processes which are not at all understood (*Karig*, 1974). The classic observations of Vening Meinesz over the Java trench indicated long ago that these were regions of pronounced local variation in gravity. Plainly more detail in the gravity field would greatly help in solving these problems, which are also of practical importance in that they apply to regions of dense population such as Japan and Indonesia.

CONCLUSIONS

There are several problem areas of oceanic tectonics where more detailed geoid such as the 10-cm altimetry from the SEASAT-A could provide would be of appreciable value. There have been several recent papers on marine geologic problems which have attempted to use gravity data in new ways (*Anderson et al.*, 1973; *Menard*, 1973; *Bowin*, 1973; *Watts and Talwani*, 1974; etc.); they all have a common note of frustration in that the gravity data which is extensively available has too coarse a resolution, while detailed data are available in only a few locations. Comprehensive survey of all oceanic geophysical variables is an economic impossibility; it would be of great value, however, to have extensive coverage of at least one variable in detail, gravity, to constitute a reconnaissance for other geophysical surveys as well as a constraint on theoretical modeling, such as *McKenzie et al.* (1974).

REFERENCES

Anderson, R. N., D. McKenzie, and J. G. Sclater, Gravity, bathymetry, and convection in the earth, Earth & Plan. Sci. Let. *18*, 391-407, 1973.

Bowin, C., Origin of the Ninety East Ridge for Studies Near the Equator, *J. Geophys. Res. 78*, 6029-6043, 1973.

Gill, A. E., Ocean Models, *Phil. Trans. Roy. Soc. London A270*, 391-413, 1971.

Griggs, D. T., The sinking lithosphere and the focal mechanism of deep earthquakes, in E. C. Robertson, ed., *The Nature of the Solid Earth*, McGraw-Hill, 361-384, 1972.

Heezen, B.C. and I.D. MacGregor, The evolution of the Pacific, *Sci. Amer. 229,* 102-112, 1973.

Jones, E.J.W., J.J. Ewing, and S.L. Eittrem, Influences of Norwegian Sea overflow water on sedimentation in the North Atlantic and Labrador Sea, *J. Geophys. Res. 75,* 1655-1680, 1970.

Karig, D.E., Evolution of arc systems in the western Pacific, *Ann. Rev. Earth Sci. 2,* 51-75, 1974.

Kaula, W.M., Global gravity and tectonics, in Robertson, E.C., ed., *The Nature of the Solid Earth,* McGraw Hill, 385-405, 1972a.

Kaula, W.M., Global gravity and mantle convection, *Tectonophysics 13,* 341-359, 1972b.

Lambeck, K., Gravity anomalies over ocean ridges, *Geophys. J. Roy. Astr. Soc. 30,* 37-53, 1972.

Leeds, A.R., Rayleigh wave dispersion in the Pacific Basin, *Ph.D. Dissertation,* U.C.L.A, 100 pp., 1973.

McKenzie, D.P., J.M. Roberts, and N.O. Weiss, Convection in the earth's mantle: towards a numerical simulation, *J. Fl. Mech. 62,* 465-538, 1974.

Menard, H.W., Growth of drifting volcanoes, *J. Geophys. Res. 74,* 4827-4837, 1969.

Menard, H. W., Depth anomalies and the bobbing motion of drifting islands, *J. Geophys. Res. 78,* 5128-5137, 1973.

Minster, J.B., T.H. Jordan, P. Molnar, and E. Haines, Numerical modeling of instantaneous plate tectonics, *Geophys. J. R.A.S. 36,* 541-576, 1974.

Morgan, W.J., Plate motions and deep mantle convection, *Mem. Geol. Soc. Am. 132,* 7-22, 1972.

Schneider, E.D., Sedimentary evolution of rifted continental margins, *Mem. Geol. Soc. Am. 132,* 109-118, 1972.

Sclater, J.G., R.N. Anderson, and M.C. Bell, The elevation of ridges and the evolution of the central eastern Pacific, *J. Geophys. Res. 76,* 7888-7915, 1971.

Watkins, N.D., and J.P. Kennett, Response of deep-sea sediments to changes in physical oceanography resulting from separation of Australia and Antarctica, in D.H. Tarling & S.K. Runcorn, *Implications of Continental Drift to the Earth Sciences,* Academic Press, 787-798, 1973.

Watts, A.B., and M. Talwani, Gravity anomalies seaward of deep sea trenches and their tectonic implications, *Geophys. J. R.A.S. 36,* 57-90, 1974.

N76 11494

SATELLITE OBSERVATIONS OF WEATHER AND CLIMATE

William W. Kellogg

National Center for Atmospheric Research
Boulder, Colorado
and
Scripps Institution of Oceanography
La Jolla, California

INTRODUCTION

The NASA program SEASAT-A, as its name implies, is addressed primarily to "both scientific and application problems in ocean surface dynamics" (*NASA*, 1974). It is clear that the conditions at the ocean surface have a pronounced influence on the atmosphere above it, so it is pertinent to view the SEASAT-A program as a new way of obtaining much needed atmospheric observations for studies of the weather and climate.

The major international thrust in global weather and climate research is the Global Atmospheric Research Program (GARP), and the observational requirements for the GARP have been quite clearly spelled out by the GARP Joint Organizing Committee (JOC) in terms of what will be required during the First GARP Global Experiment (FGGE) to define the instantaneous state of the atmosphere for general circulation studies (*GARP*, 1973). It should therefore be useful to analyze the SEASAT-A capabilities to see how well they will satisfy the FGGE objectives. This is particularly pertinent since the times of FGGE and SEASAT-A may coincide.

A second objective of GARP (referred to here as GARP-(b)) is to study "the factors that determine the statistical properties of the general circulation of the atmosphere which would lead to a better understanding of the physical basis of climate" (*GARP*, 1973). The observational requirements for GARP-(b) are generally very much less well defined than those for GARP-(a), and during July 1974 an international meeting will be held near Stockholm under the auspices of the JOC to spell these requirements out more clearly. At the time of this writing we cannot say exactly what these new specifications will be, but it is not hard to predict what they will be in general.

Here, again, we should see how much SEASAT-A is likely to contribute to GARP-(b). As it turns out, climate theory is emerging as a very important new thrust in atmospheric science, and we believe that SEASAT-A is likely to be uniquely useful here. Therefore, in what follows we will emphasize this aspect.

OBSERVING THE WEATHER

If we define "the weather" as the state of the atmosphere at any given time, then we are speaking of the "initial conditions" required to make a multi-day forecast with a general circulation numerical model. Enough experience has been gained with such models to be able to state fairly well the accuracy and resolution with which such initial conditions should be observed. From the point of view of GARP-(a) one would not need to exceed these requirements—unless all the observations and the model performances could somehow be improved simultaneously, which would be surprising. These accuracies and resolutions are generally chosen to be compatible with current numerical models and computer speeds, and consistent with each other.

With this in mind, let us turn to the FGGE observational requirements and compare them with the parameters that can be measured by

SEASAT-A. These are summarized in Table I, where we have adopted the NASA-claimed best performance for SEASAT-A (taken mostly from *NASA*, 1974, Table I), without inquiring whether this performance is overly optimistic or pessimistic (but with a slightly raised eyebrow), and without much attention to which of the instruments will make the observation. This last is in the spirit of the NASA program document's rhetoric, which says: "The sensors form a set of integrated, interactive, and mutually supporting devices whose simultaneous use brings about a genuinely synergistic effect wherein the total information derived from the sensor package is greater than the sum of the individual outputs" (*NASA*, 1974). Such a *combination* of sensor outputs and the use of auxiliary data and models would be particularly important for determining surface pressure distribution from sea surface height, and it also seems important for the determination of sea surface temperature with IR techniques.

We conclude from Table I the following: As far as GARP-(a) is concerned, the spatial resolution of all these SEASAT-A observations is far greater than needed. Before they could be useful for specifying global initial conditions they would have to be averaged for each model grid point.

The pressure distribution determined by SEASAT-A is probable not nearly accurate enough to be of value for initialization purposes. A more practical approach will be to derive atmospheric pressures from SEASAT-A wind field results and pressure data from ships.

Wind speeds are barely accurate enough for low to moderate winds. At speeds greater than 6 or 9 m/s the uncertainty of ±20° in direction will cause a vector error greater than ±2 or ±3 m/s. However, winds in the tropics are typically lighter than at mid-latitudes, and it is just in the tropics that winds have the greatest value to GARP-(a).

Sea surface temperatures are barely accurate enough, assuming the combined use of IR and microwave sensors and some spatial smoothing.

Additional information on total water vapor is probably of only marginal value to GARP-(a). (See *GARP*, 1973, p. 12).

We should emphasize before leaving this subject that the two parameters that SEASAT-A can provide with marginally adequate accuracy, namely winds in the tropics and sea surface temperatures, are considered to be of great value, and SEASAT-A will therefore probably be important contribution to the FGGE.

OBSERVING THE CLIMATE

The climate is the statistical description of the state of the atmosphere, in the form of averages for a given time of the year, of for an entire year, trends in those averages, and variances or standard deviations around the averages. Such statistics are, of course, useful in their own right for testing atmosphere-ocean models, for operational planning, for detecting trends in significant parameters, and so forth. However, the current concern with the theory of climate and the explanation of climate change requires that the statistics of the ocean and atmosphere be assembled in such a way that they throw new light on the behavior of the system that determines climate—the system consisting of the interactions between atmosphere, ocean, land, and cryosphere (*Kellogg*, 1974; *Schneider and Kellogg*, 1973; *SMIC Report*, 1971).

Still another current thrust in climate research is the effort to predict short-term deviations from the norm, or "seasonal anomalies." Some modest success in this field has been achieved, and one of the most intriguing avenues being pursued is the use of anomalies in sea surface temperature as a precursor of anomalies in the atmospheric patterns (*Namias*, 1972; *Bjerknes*, 1973; *Ratcliffe and*

Murray, 1970; *Holland-Hansen and Nansen,* 1920). There is some physical basis for believing that this may be a powerful tool for making seasonal trend forecasts, but so far the use of numerical models to quantify the relationships between sea surface temperature anomalies and pressure pattern changes have generally been disappointing (*Houghton et al.,* 1974).

Of perhaps equal interest is the extent of snow cover over land and of sea ice. Satellites have given us a unique advantage in observing changes in the distribution of snow and ice, and the inter-annual variations of this extent are bound to be important to the heat balance of the hemisphere, and hence the climate (*POLEX Panel,* 1974; *Kukla and Kukla,* 1974; *Gloersen et al.,* 1973; *SMIC,* 1971). Furthermore, passive microwave observations have even permitted studies of the age of sea ice and its morphology (*Campbell et al.,* 1973).

It will be evident that common theme in all these matters is the ocean and its circulation, since the ocean circulations must be responsible for heat transport (*Newton,* 1972) the appearance of temperature anomalies, the advance and retreat of sea ice, and so forth. Thus, the SEASAT-A observations, even though they deal entirely with the upper layers of the ocean, will be extremely valuable in contributing a better data base on ocean surface temperature, sea ice extent, and upper level currents.

Such a synoptic picture of the upper part of the world's oceans has never been obtained, and it is a prerequisite to the development of dynamic ocean models and combined ocean-atmosphere models. When the SMIC Report was written in 1971 such a synoptic description seemed so remote that no firm recommendations could be made in this area of oceanography. Quoting from that report: "We would like to be able to recommend a monitoring program for the temperature distribution and currents of the upper ocean. However, we recognize that there is at present no economical and effective way to perform such monitoring. Instead, therefore, we recommend . . . combined theoretical and observational studies to determine the best way to obtain the oceanic data required to verify joint ocean-atmosphere models . . ." (*SMIC Rept.,* 1971, p. 16).

We believe that the SEASAT-A program will mark a major step forward towards giving the observational data required for advances in ocean-atmosphere modeling; and such models are essential if we are to understand the causes of climate change and make headway in forecasting seasonal climatic anomalies. These are the objectives of GARP-(b), and they rate among the most compelling ones in the atmospheric sciences.

REFERENCES

Apel, John R., and Siry, Joseph W., 1974: *Earth and Ocean Physics Applications Program (EOPAP), Ocean Dynamics Program,* this report.

Bjerknes, J., 1973: Climatic change as an ocean-atmosphere problem. *Changes of Climate Proc., Rome WMO-UNESCO Symposium,* UNESCO, and Zone Research Series XX, Paris, 297-321.

Campbell, W. J., Gloersen, P., Nordberg, W., and Wilheit, T. T., 1973: *Dynamics and Morphology of Beaufort Sea Ice Determined from Satellites, Aircraft, and Drifting Stations,* Goddard Space Flight Center, X-650-73-194, Greenbelt, Md.

Kellogg, W. W., 1974: The earth's climate as seen from space, *Acta Astronautica, 1,* 1-8.

Kukla, G. J., and Kukla, H. J., 1974: Increased surface albedo in the northern hemisphere, *Science, 183,* 709-714.

Namias, J., 1972: Large-scale and long-term fluctuations in some atmosphere and oceanic variables, *Nobel Symposium 20 (The Changing Chemistry of the Oceans),*

ed. by D. Dyrssen and D. Jagner, John Wiley and Sons, New York.

Newton, C. W., 1972: Southern hemisphere general circulation in relation to global energy and momentum balance requirements, Chapt. 9 in *Meteorology of the Southern Hemisphere*, ed. by C. W. Newton, Met. Monographs Vol. 13, No. 35, Amer. Met. Soc., Boston.

GARP, 1973: *The First GARP Global Experiment (FGGE): Objectives and Plans.* GARP Publ. Ser. No. 11, World Meteorological Organization and International Council of Scientific Unions, Geneva, Switzerland.

Gloersen, P., Wilheit, T. T., Chang, T. C., Nordberg, W., and Campbell, W. J., 1973: *Microwave Maps of the Polar Ice of the Earth*, Goddard Space Flight Center, X-652-73-269, Greenbelt, Md.

Holland-Hansen, B. and Nansen, F., 1920: Temperature variations in the North Atlantic Ocean and in the atmosphere: Introductory studies on the causes of climatological variations. *Smithson. Misc. Coll*, *70*, No. 4, 408 pp.

Houghton, D.D., Kutzbach, J. E., McClintock, M., and Suchman, D., 1974: Response of a general circulation model to sea temperature perturbation, *J. Atmos Sci.*, *31*, 857-868.

POLEX Panel, 1974: *U.S. Contribution to the Polar Experiment (POLEX)*, Report of the Joint U.S. POLEX Panel, National Academy of Sciences, Washington, D.C.

Ratcliffe, R.A.S., and Murray, R., 1970: New lag associations between North Atlantic sea temperature and European pressure applied to long-range weather forecasting, *Quart. J. Roy Meteor. Soc.*, *96*, 226-246.

Schneider, S. H., and Kellogg, W. W., 1973: The Chemical Basis for Climate Change, Chapt. 5 in *Chemistry of the Lower Atmosphere*, ed. by S.I. Rasool, Plenum Publ. Corp., New York.

SMIC Report, 1971: *Inadvertent Climate Modification; Report of the Study of Man's Impact on Climate*, M.I.T. Press, Cambridge, Mass.

TABLE I—COMPARISON BETWEEN SEASAT-A CAPABILITIES AND GARP-(a) REQUIREMENTS FOR FGGE

Parameter	SEASAT-A / GARP-FGGE		
	Coverage	Spatial Resolution	Accuracy
Surface pressure	Along sat. track / Global	2x7 km/500 km spot	±7 mb*‡/±3 mb
Sea surface temperature	Clear sea/Global sea Cloudy sea/Global sea	1 to 7 km/500 km 100 km/500 km	±¼° to 1°‡/±1° ±1.5 to 2°/±1°
Wind speed	Oceans/Mid & high latitude	50 to 100 km/500 km	±2 m/s‡/ ±3 m/s (±20°)
	Oceans/Tropics	50 to 100 km/500 km	±2 m/s‡ / ±2 m/s (±20°)
Relative humidity	* / Global	* / 500 km	* / ±30%

* In the *NASA* (1974) report a general statement is made about water vapor content information, and improved surface pressures which can be found from the combination of wind fields derived from SEASAT-A data, and pressure readings available from ships. It is also of interest to consider the possibility of deducing atmospheric pressures from altimeter observations of the sea surface topography. It is assumed here that a 1 cm surface height change is equivalent to a 1 mb pressure change, *all corrections being perfect.*

‡ We will play the game NASA's way, but these accuracies appear a trifle optimistic.

N76 11495

CIVIL AND SCIENTIFIC APPLICATIONS OF THE GEOID

A. George Mourad
Columbus-Battelle Laboratories
Columbus, Ohio

BACKGROUND AND STATE OF THE ART

The two basic goals of geodesy are (1) Scientific goal (determination of the size and shape of the earth and its gravity field) and (2) Practical goal (determination of the geodetic control and reference datum required for surveying, mapping, economic and orderly development of land and ocean resources. In addition, since the variation in the non-uniformity of the gravity field is largely caused by mass anomalies in the earth's crust, its detailed measurement has also practical and direct economic benefits in exploration geophysics for determining certain geological structures associated with oil, gas, and minerals.

Determination of the size and shape of the earth means the determination of the geoid which is the equipotential surface of the earth corresponding to the mean sea level and to which the direction of the gravity vector is always perpendicular. This geoidal surface on which most of the geodetic measurements are referred to can be described in terms of undulations (height differences) with respect to a mathematically defined ellipsoidal surface on which most of the geodetic computations are based.

Satellite Altimetry and particularly SEASAT can determine the geoid surface to an accuracy better than any other presently known method. The present methods for determining the geoid depend on the knowledge or measurement of the detailed gravity field all over the earth and the use of satellite perturbations to describe the general field. Measurement of the gravity field all over the earth requires the use of land-based, shipborne, airborne and ocean bottom gravity instruments. To get worldwide coverage with sufficient accuracy in geoid determination may require something like 20 ships operating continuously for about 20 years to, perhaps, achieve an accuracy of the order of 1-3 meter. Present knowledge of the geoid on a world wide basis is probably not better than 3-30 meter at best.

SEASAT-A APPLICATIONS

SEASAT-A can be used for determining the geoid to much higher accuracy on a world wide basis and in a relatively short time. Two basic objectives can be considered:

(1) Determination of the geoid to at least 1 meter. This accuracy will satisfy most geodetic requirements for applications purposes.

(2) Determination of the geoid to better than 1-meter (ultimately 10-cm) although not a geodetic objective but rather an oceanographic objective required for measurement of sea surface topography and sea slope, quasi-stationary departure from the geoid, ocean circulation, air and sea interaction, etc. The geodesy objective in this case will be to define a reference equipotential surface as a means by which the oceanographic requirements can be achieved.

SEASAT-A (GOAL—AT LEAST 1-M GEOID ACCURACY)

(1) This should be significant to geodesy for determining the size and shape of the earth and a unified datum and coordinate system on a worldwide basis. All geodetic reference datums, their triangulation and trilateration networks can be based on the same system with an accuracy of 1 meter. Such a worldwide accuracy cannot be practically

achieved with present methods. Civilian control requirements on which land and ocean surveying, mapping, tying various navigation systems, and engineering development are based will benefit. The objectives of the new adjustment of the North American datum (NAD) is ultimately 1-m. The extension of control points and determining their three dimensional coordinates to offshore areas as well as determination of national and international marine boundaries must be established in the same system. The NAD is already being extended to offshore areas using the oil companies, platforms up to 120 miles from shore using geodetic satellite receivers (Geoceivers) and navigation satellites thus placing their coordinates already on a geocentric system.

(2) Accurate knowledge of absolute deflection of the vertical at sea could be of importance if combined with marine geodetic control for determination of the absolute orientation of all national datums including the NAD.

(3) Knowledge of the geoid to 1-m accuracy should at least define the mean sea level on a worldwide basis to be of help particularly in areas of land subsidence where the land subsides in certain areas like Long Beach, California, and Houston on the order of about 0.5 to 1 ft. per year. Such subsidence could cause considerable damage to structures such as expensive industrial and residential homes near the coastlines. The tide gage on which leveling is based is subject to subsidence.

(4) Improved determination of the earth gravity model will result in better determination of satellite orbits and location of tracking stations from which satellite orbits are also often computed.

(5) Gravity anomalies derived from SEASAT-A could provide reconnaissance information which might potentially become a useful tool for oil and mineral explorations. Geologic structures such as faults, salt domes and other features favorable for oil and gas exploitation may be identifiable when combined with other geophysical methods such as magnetic and seismic. This contribution for the long term energy crisis may become increasingly important. Although we know theoretically the basic technique by which we can convert altimetry data to gravity anomalies, considerable studies and analysis must be done for practical application. Further knowledge of the geological structures, their composition and origin are of scientific importance.

(6) Present geopotential models are not now known accurately to better than 15° x 15° field. Even here many terms of high degree and low order are poorly represented. Such knowledge can resolve the gravity field to about 12° x 12°; a 1-m geoid could provide perhaps a 1° x 1° resolution of the gravity field which should approximately correspond to a geopotential model of about 180 x 180 which cannot be obtained practically by other means. Such improved knowledge of the gravity field when combined with accurate coordinate systems, will contribute to earth physics, plate tectonics, earthquake mechanism and polar motion studies.

SEASAT-A (10-CM GEOID GOAL)

The need to investigate the oceans as a whole and as an integral part of land and atmosphere is well recognized. Although many oceanographic measurements can benefit from knowing even 1-m geoid on a world wide basis; most of the oceanographic and other application areas that will benefit the most from a 10-cm geoid are outlined below.

Resolution of the controversy in the difference between the mean sea level slope as determined from spirit leveling by geodesists and by steric measurements by the oceanographers particularly along the U.S. East and West coasts.

Establishment of a 10-cm absolute geoid will be an ideal reference datum for all continental leveling networks.

Dynamic (temporal) variations in the shape of the oceans are due to many factors including:

(a) Barometric pressure, gravity variation, heat and salt content and their seasonal variations and their effect on the shape of the sea surface can be determined. Such variations are of the order of 10-cm to several meters.

(b) Storm surges, which describes the local build-up of water due to distant violent storms (such as hurricanes and typhoons), could cause damage and wave heights of the order of several meters when they hit coastal areas. Their prediction and direction of movement could be of importance not only for coastal areas but also for maritime ship operations.

(c) Tsunamis (seismic sea waves)—their amplitudes in the open ocean vary from perhaps a few centimeters to about one meter. These have large wavelengths of the order of several thousand km with about 1-hour period. If they are accurately detected in advance they could prevent false alarms. The tsunami wave velocity decreases and its wave height increases as it approaches the coasts. If a tsunami reaches coastal areas, it could have wave heights of several tens of meters and cause considerable flooding and damage to coastal areas.

(d) Sea slope due to ocean currents could cause local rise of water across the current on the order of 1-meter This is largely due to coriolis forces. Accurate knowledge of this will help both oceanography and geodesy.

(e) Ocean wavelengths of the order of 1-cm (ripples) to about 1000 m for swell may be detected. Sea states of significant wave heights up to 30 meters will be detected by SEASAT.

(f) Tides—open ocean tide is difficult to measure at present. Of importance is the separation of ocean tides from earth tides. The combined sun and moon effect could be of the order of 78 cm. Although some of this effect may be canceled by other factors, its knowledge and perhaps the correlation with bottom topography, thermal ocean, and air/sea interaction could lead to many scientific studies and applications.

PROBLEM AREAS

The most important objectives of SEASAT are that SEASAT must achieve the requirements of the end-users (both scientific and commercial). The ultimate end-user requirements of a 10-cm geoid will depend simply on the solution of three major problems. These are (1) orbit accuracy problem, (2) instrument accuracy problem, and (3) verification and validation problem. So far, only instrument precision of the altimeter of 7 to 10 cm appears to be possible from an instrument design point of view. Orbit accuracy may approach 1-2 meters provided sufficient tracking system accuracy can be achieved. Elimination of effects of orbit inaccuracy may be achieved through the solution of the third problem which, so far, has received the least consideration. The verification problem will involve the establishment of a test area consisting of a few marine geodetic control points for which the three-dimensional coordinates can be determined through satellite and surface systems. The use of astrogravimetric techniques with such control points could provide an absolute geoidal profile correct in scale, shape, and orientation to about 1-meter with present technology. Such a geoid could provide the validation required for detecting instrument drift and other factors and would eliminate the residual effect of orbit inaccuracy such that at least 1-m geoid can be achieved.

Further improvement of techniques both in orbit tracking and surface validation methods will further improve SEASAT accuracy so that ultimately a 10-cm geoid can result to meet the end-user requirements. We strongly feel that the third problem must receive more

attention on the part of NASA, the user agencies, and other user communities.

Skylab altimetry investigations to date confirm the importance of knowing accurate orbit and the geodetic ground truth (validation and verification problem). For example, the results indicated that, when the altimeter is functioning properly, a priori knowledge of geoid heights affects the scale and not the shape of the geoid. The better the a priori value of the geoid height is known, the better can the scale be determined.

C. 2

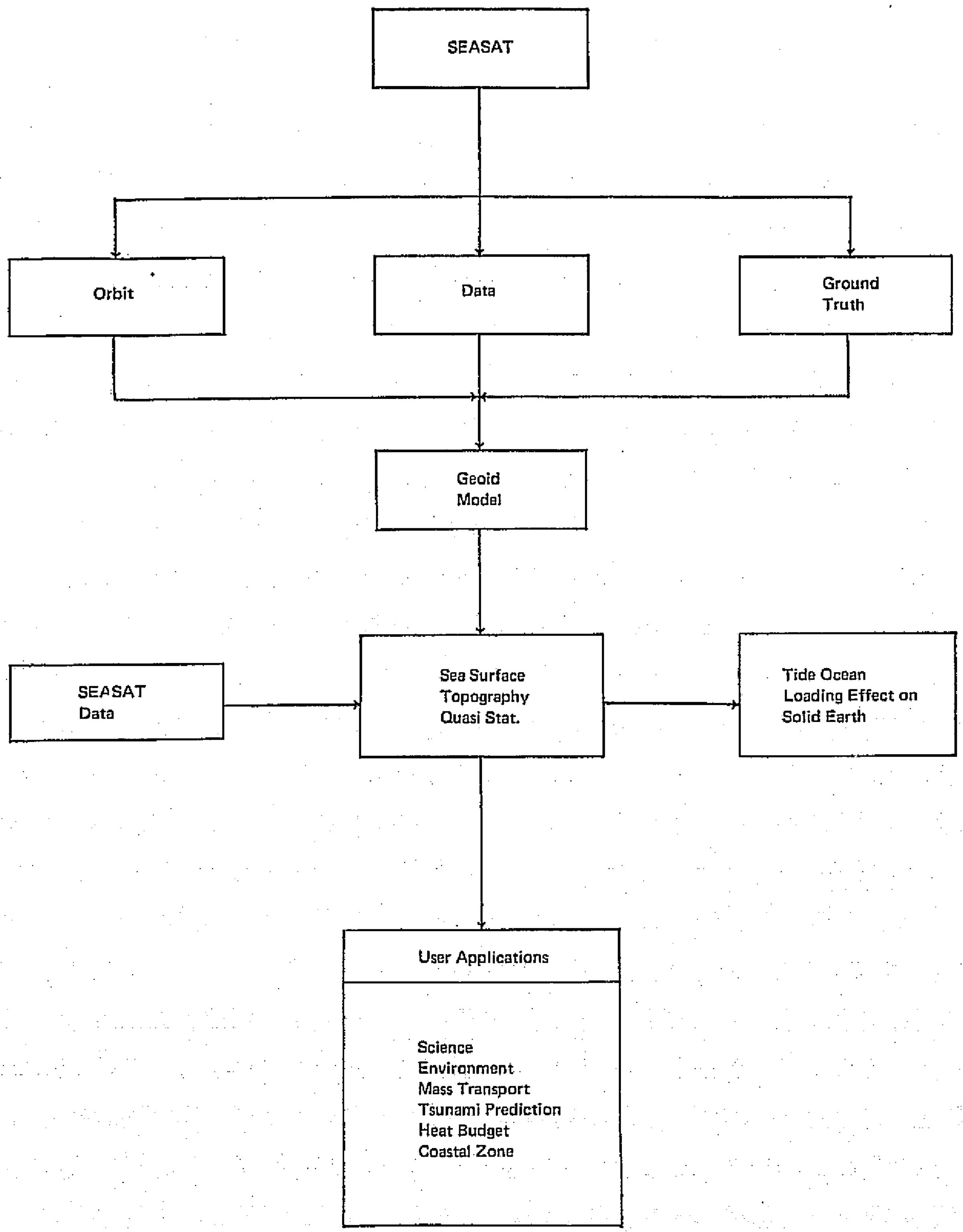
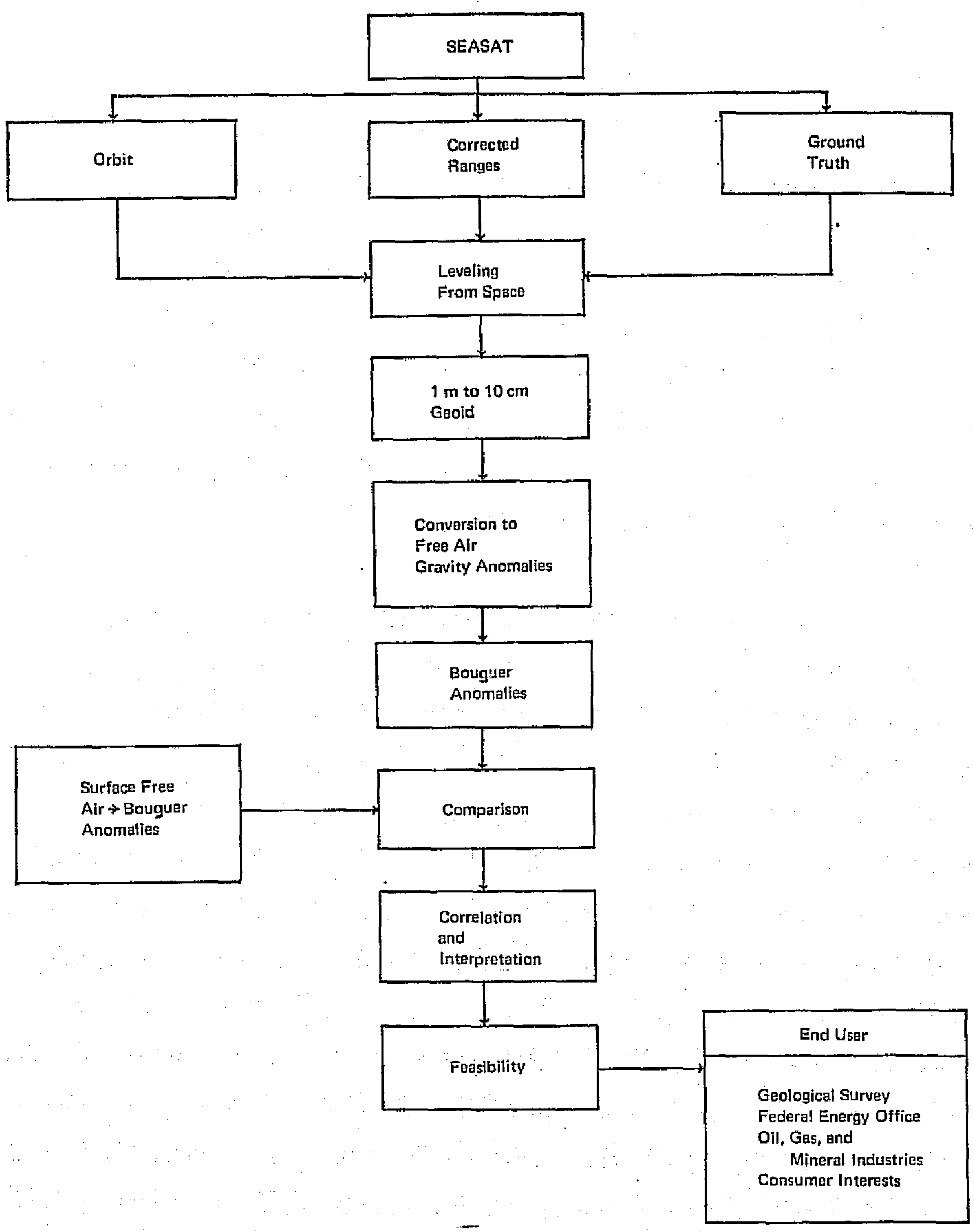

SEASAT
Orbit
Data
Ground Truth
Geoid Model
SEASAT Data
Sea Surface Topography Quasi Stat.
Tide Ocean Loading Effect on Solid Earth
User Applications
Science
Environment
Mass Transport
Tsunami Prediction
Heat Budget
Coastal Zone

Figure 1.



SEASAT
Orbit
Corrected Ranges
Ground Truth
Leveling From Space
1 m to 10 cm Geoid
Conversion to Free Air Gravity Anomalies
Bouguer Anomalies
Surface Free Air → Bouguer Anomalies
Comparison
Correlation and Interpretation
Feasibility
End User
Geological Survey
Federal Energy Office
Oil, Gas, and Mineral Industries
Consumer Interests

Figure 2.

N76 11496

EXPLOITATION OF SEASAT-A OCEANOGRAPHIC MEASUREMENTS FOR NAVY R&D APPLICATIONS

V. Noble
Naval Research Laboratory

INTRODUCTION

SEASAT-A oceanographic measurements will be applicable to a wide range of Navy R&D activities. These efforts include basic research in the environmental sciences, exploratory development in sensor design and measurement technology, and advanced development of environmental analysis and prediction products for operational fleet support. Many facets of the R&D effort are interdependent so that the effectiveness of the SEASAT-A experiments are a complex function of capabilities and developments in several areas.

The purpose of this discussion is to identify some of the interactions and trade-offs to be considered. Specific scientific problems, and applications experiments, will be described as topics of separate contributions by disciplinary experts.

ENVIRONMENTAL CORRECTIONS FOR GEODESY

The design goal for measurement of ocean topography is a precision of 10 cm. Data reduction of the altimeter data requires removal of time-varying environmental factors in order to determine the local structure of the gravity field of the earth. These are five significant environmental factors that can each contribute perturbations of the ocean topography (as measured by the altimeter) of the order of 1 meter with reference to the true local geoid. These factors are variations of the index of refraction through the atmospheric column, ocean level changes due to the wind and pressure fields of weather systems, range measurement changes due to the changes of the roughness statistics of wave fields, surface elevation changes due to currents, and ocean level changes due to tides.

Operational data fields from the Fleet Numerical Weather Center (FNWC) will be used during the calibration phase to provide correction terms (atmospheric structure, wind, pressure, and wave fields) and to calibrate the SEASAT-A instruments for a self-correction capability. For routine acquisition of geodetic data, the microwave radiometer will provide data for corrections for variations of atmospheric transmission, and the slope of the radar range signal will provide a measure of the ocean roughness statistics. The microwave radiometer and/or scatterometer will be used for wind/pressure field measurements. Measurements of the Sea Surface Temperature Patterns will assist in the location of some major current systems.

Data processing methods and experience from GEOS-C (scheduled launch for December 1974) will be used as the approach to the SEASAT-A experiment. It is necessary that the calibration phase of the SEASAT-A measurements are carried out expeditiously to verify system performance and to calibrate the sensor system (using available ground truth) to establish performance limits for self-correction for time-varying environmental factors. Data from all of the SEASAT-A sensors will be used during the calibration phase. SEASAT-A sensor data will be merged with available ground truth data to establish performance limits. Reduction of the altimeter data will be carried out in a continuous mode to provide corrected data for geodetic calculations at Naval Weapons Laboratory. SEASAT-A data will need to be processed on a continuous basis in order to manage data

flow; monitor data quality; provide feedback between ground truth data sources, self-correction sensor data, and radar altimeter output; and facilitate close monitoring of the data product so that supplemental ground truth support may be provided for repeat coverage of critical areas.

SEASAT-A sensor data are required at the geodetic data processing facility within five days of acquisition. Due to the constraints of the orbit dynamics only two or three repeat measurements of the ocean topography on an 18 km grid will be made within the design life of the satellite. Therefore, close monitoring of the data is required to schedule supplemental ground truth support by airborne or ship surveys in critical areas. For example, airborne BT soundings may be required to investigate the possible existence of ocean currents, or ship surveys may be required to investigate the possible location of sea mounts in regions where ocean topography anomalies are detected.

SENSOR PERFORMANCE EVALUATION

Detailed evaluation of SKYLAB altimeter data has established the potential of satellite radar altimetry for measurement of ocean topography. The GEOS-C experiment will extend the technique evaluation and will establish criteria for calibration, data processing, and performance evaluation of the SEASAT-A system. Adaptive range-tracking algorithms must be established to optimize the altimeter measurement capability to achieve the design goal of 10 cm precision. Methods must be confirmed for the determination of sea state from the slope of the altimeter range signal to establish self-correcting procedures as a function of sea state.

The SEASAT-A sensor system, with a multi-frequency passive microwave radiometer, radar scatterometer, and radar device for measurement of directional wave spectra, presents a unique opportunity for comparison of candidate systems for oceanographic measurements from satellites. During the calibration phase of SEASAT-A, intercomparison of these sensor systems, and calibration against ground truth data, will serve three principal functions. The first objective is to establish data processing methodology for routine correction of the radar altimetry data to remove time-variant environmental factors from the radar altimetry measurement. The second objective is to establish criteria for the design of an optimum (precision, dynamic range, data processing requirements, weight, power, cost) system for operational measurements of atmospheric structure, surface winds, sea surface temperature, and directional wave spectra. The third objective is to verify sensor performance capabilities, and to determine data processing procedures for: evaluation of operational analysis and prediction products, to sustain prediction models in an operational demonstration, and to provide data input for basic research investigations in the environmental sciences.

The sensor performance evaluation will be an integral part of the procedure for establishing techniques for definition of methods for removing time-variant "noise" signals from radar altimeter measurements of ocean surface topography.

OPERATIONAL DEMONSTRATION

Sensor performance, data reduction algorithms, and data handling procedures will be established within the "calibration phase" of SEASAT-A. The calibration phase is estimated to extend thru the first six months after launch. The operational data processing grid used by FNWC is determined by the current availability of ship reports (approximately 2000 reports/day concentrated along shipping lanes) and resolution requirements for the analysis area. During the calibration phase, instrument performance will be confirmed, and data processing algorithms will be developed for demonstration of the potential for SEASAT-A sensors to provide data inputs

for operational oceanographic analysis and prediction products.

Principal emphasis for the operational demonstration will be on utilization of surface wind and wave spectral data as input for the wave spectrum predictions at FNWC. SEASAT-A surface wind measurements will be used to supplement ship observations to provide the basic driving force for the wave predictions. Wave spectrum measurements will be used to provide boundary conditions for the wave forecast area. For example, ocean waves and swell generated by Southern Hemisphere storms contribute to the initial condition wave spectra at the equatorial boundary of the Northern Hemisphere wave model.

SEASAT-A data for the operational demonstration will flow through the Satellite Data Processing Center at FNWC. Operational analysis products are generated at 6-hour intervals using data observed within 3 hrs of the nominal product time. Therefore, for an operational demonstration, to supplement data inputs as an evaluation of potential operational methods to sustain oceanographic prediction products, data must be continuously available to the Satellite Data Processing Center. To be of value in an operational demonstration, SEASAT-A observations reaching the Satellite Data Processing Center can be no more than 6 hours old.

It is not practical to carry out short operational demonstrations for a number of reasons. Time scales of motion of large weather systems in global models are of the order of one to two weeks. For spectral wave forecasts, determination of directional wave spectra at computational grid points depends both upon the local wind field and upon wave and swell components propagated in from distant generating sources. A significant resource commitment is required for preparation of software to inject SEASAT-A data into the operational prediction process, and short on-off periods of data availability cause perturbations of the mechanics of the operational process.

Due to the value of the spectral wave prediction program for ship routing, geodetic ground truth, prediction of surf in coastal areas, and other Navy operations, it is important that a significant operational demonstration and evaluation be carried out. The demonstration period should be sufficiently long with respect to time-scales of global weather systems, time- and space-scales of representative Naval operations, and extend through seasonal variations to establish design criteria for subsequent operational systems. The follow-on system must be optimized for sensor selection, precision and resolution of measurement, frequency of coverage, data handling facilities, and computational software to achieve over-all system economies consistent with mission support requirements. Therefore, during the aircraft flight test program, and during the calibration phase of SEASAT-A, careful appraisal of sensor performance must be carried out, data reduction algorithms developed, and data communications established for the operational demonstration phase of the effort. Then, the operational demonstration phase would consist of continuous utilization of at least a minimum sub-set of data (e.g., surface winds and wave spectra) during the remaining life of SEASAT-A (6 months or more).

RESEARCH APPLICATIONS

SEASAT-A will provide a measurement capability to supply quantitative data that will permit evaluation and improvement of theoretical models for the description and prediction of dynamic oceanographic processes and for the study of geographic areas. Radar altimetry data will be used for evaluation of tidal prediction models. Altimetry and passive microwave Sea Surface Temperature data will be used for evaluation of large-scale circulation models such as have been devel-

oped for the NORPAX Study. Passive microwave ice imagery will be used for all-weather observations to assist in evaluation of large-scale ice motion studies such as AIDJEX and the Navy Marginal Ice Zone studies. Passive microwave measurements of sea surface temperature and atmospheric water content will assist in marine fog studies for Navy programs. Surface wind field measurements will be used as a data source for evaluating and improving marine weather prediction models. Measurements of directional wave spectra will be used for continued development of wave prediction capability and forecasts of near-shore surf/storm surge conditions by the Naval Weather Service.

High-resolution radar imagery will permit acquisition of all-weather data for study of the complex dynamics in coastal regions and within sea ice fields. These regions are characterized by small-scale processes of high energy intensity such as beach erosion; formation and movement of sand-bars and spits; formation and movement of ice ridges, leads, and polynas; complex local circulation patterns; and by fine-scale, significant changes in the wave/swell/surf patterns due to the influence of local topography, damping by free-floating ice, and the influence of tides and storm surge. Study of these areas is further complicated by the probability of occurrence of clouds and fog. The all-weather observation capability of an imaging radar will tend to compensate for the coverage limitations because of the narrow swath width.

SUMMARY

This discussion has described the breadth and interdependency of basic research, exploratory development and operational demonstration potentials for exploitation of SEASAT-A data. Detailed discussion of experiments in specific areas will be provided in separate contributions by disciplinary specialists. The most important aspect of this discussion is the indication of the need for a closely integrated experiment to maximize the productive output for all participating users.

N76 11497

THE SCIENTIFIC JUSTIFICATION FOR OBTAINING OCEAN WAVE DATA OF VARIOUS KINDS WITH SEASAT-A*

Willard J. Pierson
The University Institute of Oceanography
The City College of the City University of New York

INTRODUCTION

There are three candidate instruments for obtaining some kind of spectral wave information with SEASAT-A. There is another instrument that will provide data on wave heights, if properly designed, in addition to its prime function of altimetry. The altimeter data on wave height can be obtained every 50 or 100 kilometers along the subsatellite track routinely. The spectral data may be one of two different forms depending on which of the three candidate instruments is finally chosen. The contribution to the scientific study of wind generated ocean waves and swell by combinations of these instruments on SEASAT-A is the subject of this paper.

THEORY OF THE DIFFERENT INSTRUMENTS

Over the deep ocean, for an area tens to hundreds of kilometers on a side, the sea surface can be considered to be a function of space and time, $\eta\ (x,\ y,\ t)$, that does not change its essential statistical characteristics as defined by a wave spectrum. However, in the global sense, the properties of this wavy surface vary markedly from place to place over the ocean and from hour to hour at any fixed point. Individual waves over 25 meters high, and sequences of waves, where ten percent exceeded 18 meters in height for a half hour or more, have been measured. SEASAT-A will be capable of gathering correct data on these conditions on a routine global basis.

The variation of the higher and longer gravity waves from place to place as time goes on is caused by the synoptic scale variation of the winds over the ocean. Large areas of strong winds generate high waves over large areas. These storm waves then spread out and travel across the oceans thousands of miles as swell producing high waves even in areas where there are no winds.

There are various ways to summarize the properties of the waves on the ocean. The simplest is to describe the square of the wavy surface averaged either over a sufficiently long time, or along some long enough line, or over large enough areas as follows:

$$\sigma^2 = \frac{1}{T}\int_0^T (\eta(t))^2\,dt$$

$$= \frac{1}{L}\int_0^L (\eta(x^*,y^*))^2\,dx^*$$

$$= \frac{1}{L}2 \int_0^L \int_0^L (\eta(x,y))^2\ dxdy$$

In the above expression the x^*, y^* coordinate system can be oriented in any way for the area being analysed. The variance of $\eta\ (x,y,t)$ is the most important single number to describe the waves, and, for example, the average of the heights of the one-third highest waves to pass a fixed point, called the significant wave height, is given by the following expression

$$\overline{H}_{\frac{1}{3}} = 4\,\sigma$$

*This paper and the following one were prepared for the SEASAT-A User Agency Committee under the sponsorship of Contract NAS 5-20041, with the Goddard Space Flight Center.

The most complete description of $\eta(x,y,t)$ within a linear theory of the waves, would be given by observing, $\eta(x,y)$ at some instant of time for a properly chosen area, and obtaining the spectrum of this portion of the surface so as to resolve the variance, σ^2, into spectral wavenumbers as in

$$S(l,m) \qquad \text{or } S(\mathrm{k})$$

where l is the wave number on the x direction and m is the wavenumber in the y direction. The spectrum, $S(l,m)$, has the property that

$$\sigma^2 = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S(l,m) \; dl\,dm$$

There is in general a 180° ambiguity in the direction of wave travel that has to be resolved by means of other considerations.

Synthetic aperture radar images of the sea surface in deep water can quite possibly yield spectra for a chosen set of sites daily on a global basis. Recent theoretical work strongly suggests that this is the case, and experiments are currently under way to study synthetic aperture radar wave images in terms of various theories and in comparison with wave data obtained by Flip.

The other two candidate instruments essentially scan along a line and do not have the capability to obtain two dimensional images. An aircraft proof of concept demonstration of this instrument concept has not yet been obtained. The sea surface can always be treated in a coordinate system such that x^* is in the direction of the scan as in $\eta(x^*,y^*)$.

The vector wave number spectrum is then of the form

$$S(l^*,m^*)$$

Since knowledge of the sea surface is obtained only in the x* direction, the spectrum that would be found is given by

$$S(l^{**}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G(m^*,l^*)\, S(l^*,m^*)\, dm^* dl^*$$

The function $G(m^*,l^*)$ is a function of the antenna gain, pulse width, and beam geometry. It can be approximated by a very narrow function of m^* near $m^* = 0$ and by slight smoothing over l^*. The spectrum that results can be approximated by

$$S(l^*) \cong \int_{-m^1}^{m^1} S(l^*,m^*)\, dm^*$$

There is an ambiguity in the wave direction in such an estimate that folds values of the spectrum for $-l^*$ over to $+l^*$ and yields the sum, so that the final result, defined for $0 < l^{**} < \infty$, is

$S_1(l^{**}) = S_1(l^{**}) + S_2(l^{**})$ where
$S_1(l^{**}) = S(l^{**})$ for $l^* < 0$ reflected at $l^* = 0$ and
$S_2(l^{**}) = S(l^{**})$ for $l^* > 0$

These data could be quite useful since they are essentially one dimensional slices through a two dimensional function and provide data on those waves traveling toward and away from the spacecraft.

Data Rates and Coverage

For the altimeter wave height measuring mode, data on wave height could be recorded every so many kilometers along the subsatellite track. Every 55 km (or every 30 nautical miles) might be a convenient choice. The variation of wave height with distance is small enough so that points closer together would not provide much new, useful information. Measurements twice as far apart would also probably be satisfactory. For a 55 km spacing and an orbit entirely over water there would be 720 measurements, and for about 13 orbits per day, there would be 9360 measurements. If about 70% of each orbit were over water on the average, there would be about 6550 observations in one day.

The single scan method for obtaining $S(l^{**})$ could produce values of this spectrum at a

similar rate over very nearly the same areas, so that again about 6000 spectra would be obtained each day. Perhaps values for $S(l^{**})$ at 50 equally spaced values of l^{**} to 20 bit accuracy would be obtained each day.

Finally, the synthetic aperture radar data may be processed in two different ways, one to produce spectra for waves in deep water, and the other to produce images of waves being refracted on coastal waters. The use of SAR images for coastal waters will be discussed later. For the deep ocean, there is the danger that too much data may be obtained. A convincing set of reasons for obtaining about 500 spectra of the form $S(l,m)$ will be given in this discussion. The SAR is the design instrument for the final SEASAT-A version.

Uses of a Climatological File

Data on waves are routinely collected by ships at sea. Wave heights, periods and dominant direction of travel are recorded in a special code by many ships at 00h, 06h, 12h and 18h G.M.T. These measurements are collected, stored at national data centers, and used to produce statistical summaries of the waves for the various areas of the oceans. The cost of collecting, storing and analyzing data of this kind runs to the millions of dollars annually.

Also, a very small number of weather ships have wave recorders that measure the rise and fall of the sea surface as a function of time at a point. These wave records can be analysed so as to obtain still another kind of spectrum, the frequency spectrum, $S(\omega)$. Then spectra have been studied and used to develop wave forecasting techniques and to aid in the design of ships. Wave records of this nature are obtained routinely at about four or five locations in the North Atlantic and at one location on the North Pacific.

A consortium of oil companies has used wave recorders on their drilling rigs to collect a large amount of wave data during hurricanes in the Gulf of Mexico. These data are to be released shortly. This substantial effort to obtain wave data in these two ways is a measure of the need for, and the value of, it. Yet, this level of effort is inadequate for the future needs of the United States and the other nations of the world.

The reports from ships are estimates of the wave conditions. They are not measurements. Also, they are concentrated along shipping lanes and do not adequately describe conditions on a uniformly spaced grid over the oceans. Moreover, they tend to be substantially in error, and the data obtained, prior to a few years ago, had built-in biases that tended to group reported wave heights near 5 meters and 10 meters and to report high waves inadequately. In one study, in which these estimates of wave heights were compared with measured wave heights, the estimates frequently differed by a factor of two, either too high or too low, from the measured values. Only about 1200 or so, ships report wave conditions in this way each six hours, mostly in the Northern Hemisphere.

The shipborne wave recorder data are of high quality and have proved invaluable for many scientific investigations. However, the number of ships and their locations is just too few to provide an adequate data base.

The instrument complement on SEASAT-A would replace the crude estimates of wave conditions made by most ships with accurate measurements of wave height. The measurement of waves at a few locations to yield $S(\omega)$ would be replaced by measurements of waves that would yield either $S(l^{**})$ or $S(l,m)$ at a large number of locations daily. About 1200 estimates of wave conditions each day concentrated in the Northern Hemisphere would be replaced by about 6000 measurements fairly uniformly spaced over the entire earth. If a synthetic aperture radar were used, spectral estimates, $S(l,m)$, could be obtained for hundreds of different areas daily compared to the four or five sites for which spectral data are now obtained.

These measured wave conditions can be collected and archived on a day to day basis. For a year of operation, over 2 million measurements of wave height would be made. If the imaging radar were to yield only 500 spectra ($S(l,m)$) per day, a total of about 180,000 would be accumulated in one year.

For the first time, uniformly spaced measured values would replace estimates concentrated on shipping lanes and the few measured values from ships that yield climatological data for only a few sites on the ocean.

These archived values have many uses. They would provide data on how high the waves are in storms of varying intensity and on conditions over the continental shelves for areas for the potential installation of a variety of offshore structures. The design of new kinds of ships, such as the surface effect ships and large hydrofoils, would be aided by these data. There is no substitute for correct measurements of wave properties collected routinely over many years on a global basis.

Scientific Uses of the Wave Data

The modern way to forecast waves is to apply the physical laws for the generation of waves by wind, the dissipation of waves by opposing wind seas, and the propagation of waves to a set of grid points over the oceans using the observed wind field to describe the waves at particular time and forecasted wind fields to predict what the waves will be like several days into the future. Under the sponsorship of the U.S. Navy Oceanographic office and the National Aeronautics and Space Administration, a global numerical wave forecasting model has been developed and put into operation at the Fleet Numerical Weather Facility at Monterey with the help of the staff there. About 450 spectra are computed for the North Atlantic and 900 computed for the North Pacific every three hours. Each spectrum is described by 180 numbers. If the spectrum is represented by a function in the ω, Φ plane, the numbers in the forecast represent integrals over twelve 30 degree direction bands and variable frequency bands of the form:

$$S_{ij} = \int_{\theta_1}^{\theta_2} \left[\int_{f_1}^{f_2} S(f, \theta)\, df \right] d\theta$$

This numerical spectral wave forecasting model is presently being tested and verified against the few available frequency spectra from shipborne wave observations. Another model will also be developed and compared with this model. For the one that proves superior, it is planned to use several years of past wind data over the Northern Hemisphere to compute what the wave spectra were like. Such computations are called "hindcasts" or wave specification calculations. They will serve as a substitute for the data that will be obtained by spacecraft such as SEASAT-A in the future. Over the course of time, SEASAT-A and its operational successors would provide actual measurements to replace these "hindcasted" spectra. Specialized numerical spectral wave forecasting models have been developed for the Gulf of Mexico for hurricane conditions, and for the Mediterranean Sea so as to take care of the smaller scales of these bodies of water. Higher spectral resolutions and shorter time steps are needed.

There will always be the need to forecast wave conditions for as many days as possible into the future. The improved wind measurements from SEASAT-A will permit improved weather forecasts and these in turn will permit improved wave forecasts. The present wave forecasting models cannot be completely verified using shipborne wave recorder data. The forecasted spectra should be verified by spectra of the form $S(l,m)$, not simply $S(\omega)$.

The present numerical spectral wave forecasting models are quite good; they incorporate many physical features of the generation and propagation of waves, but not all of the variously proposed theoretical features of

waves. However, there is always room for improvement in any numerical model of a physical phenomenon of the oceans because there are always increasing levels of complexity that need to be modeled. At present, though, the problem is one of an adequate verification data base upon which to build improved numerical spectral forecasting models. The measurements to be made by SEASAT-A would provide the kind of data needed to develop greatly improved numerical wave forecasting models by providing a means to determine the errors in the present models.

SAR data, transformed to spectra on the deep ocean, can be used to improve wave forecasting. If spectra are obtained for areas where the waves are predicted to be high, where certain nonlinear effects are predicted to have occurred, and where swell dispersed by various amounts is forecasted, over the course of many days, constant differences between spectral forecasts and SAR derived spectra can be used to locate the theoretical source of these differences and correct for them in the forecasting model. This is the way that numerical weather forecasting models have been continuously improved over the past several decades and this is the way operational versions of wave forecasting models can be upgraded.

All forecasts degrade as the range is extended, and the interaction between weather forecasts, the wave specification calculations, and wave forecasts is complex. SEASAT-A data would also provide a check on how well a model describes the waves based on observed past and present winds so as to isolate separate sources of error in the forecast caused by poor initial value specification and by degraded wind forecasts with increasing time. If high quality four day forecasts are achieved, other users will want six day forecasts, and if they are achieved, still others will want twelve day forecasts. The forecast problem for both waves and weather, and eventually other oceanic variables, is an open ended problem that builds on its own past successes and continuously strives to increase the range of validity of the forecasts.

Not too many spectra of the form, $S(l,m)$, would be needed. Several hundred a day over the deep ocean would be adequate. If the forecast model were to verify well at this number of points each day for a number of different storm patterns, it could be concluded that any unobserved points would also have verified equally well.

Coastal Problems

When the depth of the water becomes less than half the length of a spectral component in a wave spectrum, the speed of the component is affected by the depth. The shallower the water, the slower the wave travels. Complex offshore submarine topography turns the waves away from deeper regions and focuses them at shallower regions. There are shallow areas off the coasts of parts of the continents, called continental shelves, that are one hundred to several hundred kilometers wide. The depths in these shallow areas are complex, and the waves are refracted in ways both difficult to describe and to compute.

All structures to be built in such shallow water areas require design wave data so that the structures can withstand the forces on them produced by the high waves during a storm. Also the continued action of the lower waves can erode away the material around a structure's base and cause it to collapse. With the many proposed offshore structures all around the coasts, the problem of adequate designs for them will become increasingly more pressing during the next few decades.

One area, studied in the past, and under renewed theoretical analysis, is the New York Bight, especially as affected by the Hudson Submarine Canyon. Offshore sites just ten or twenty miles apart along the coast can be exposed to waves a factor of ten times higher at one site than at the other at times.

During selected conditions with appropriate offshore deep water waves, SAR images can be obtained that will provide verification data for wave refraction studies in shoal water. Moreover, potential sites all over the world can be surveyed as to wave refraction effects for preliminary, and even perhaps final, design considerations. The actual images will have to be recovered because the waves become shorter and change direction as the water becomes shallower, so that the concept of a spectrum representative of an entire area is not applicable.

SAR images require a high data transmission rate to the earth from a spacecraft. It does not seem necessary to run such a system continuously while the spacecraft is over the ocean. Large ocean areas are relatively uninteresting, and others become interesting only during particular meteorological conditions. A scientist familiar with the needs of the user community could rather easily select about 500 sites per day on a global basis for obtaining SAR images, some over the deep ocean and others at coasts so that in the course of each year a global data base of 180,000, or so, coastal refraction patterns and deep water wavenumber spectra could be obtained.

N76 11498

THE SCIENTIFIC JUSTIFICATION OF A RADAR SCATTEROMETER AND A PASSIVE MICROWAVE SYSTEM ON SEASAT-A

Willard J. Pierson
The University Institute of Oceanography
The City College of the City University of New York

DESCRIPTION OF SENSORS

The purpose of these two systems is to determine the winds over the ocean. The passive system may also provide data on precipitation over the ocean and sea surface temperature through clouds. They complement each other. The radar scatterometer will sense those sea surface properties that define the winds over the ocean through clouds so thick and so wet that the passive microwave system will have detected only the cloud properties. Both wind speed and direction can be found from the combined data to be obtained.

The data to be obtained by SEASAT-A will be the equivalent of about 20,000 ship reports each day, of wind speed and direction uniformly spaced along the swath covered by the spacecraft over the 70% of the earth covered by the oceans. Combined with a few scattered ship reports of wind direction and atmospheric pressure at the sea surface, these winds will make it possible to compute the atmospheric surface pressure field over the entire ocean, especially over the oceans of the southern hemisphere, to a high degree of accuracy.

USE OF THE DATA

This atmospheric sea level pressure field then specifies the conditions in the planetary boundary level, or for numerical weather prediction models, the properties of the 1000 millibar surface. This surface pressure field, or the equivalent 1000 millibar surface, then serves as the long sought elusive REFERENCE SURFACE for VTPR soundings so that the vertical structure of the entire atmosphere can be specified for numerical weather prediction models.

The height contour pattern of the planetary boundary layer 1000 millibar surface is complicated and consists of closed depressions and elevations corresponding to the highs and lows of conventional weather charts. If it can be specified correctly, the bottom of the atmospheric soundings obtained over the oceans by the VTPR infrared sounding system, now operational on NOAA spacecraft, can be correctly related to this 1000 millibar REFERENCE SURFACE and an integration of the VTPR computed sounding then yields the heights of all the other constant pressure surfaces used in numerical weather prediction models. The most difficult part of the present use of these VTPR soundings is the determination of conditions near the sea surface, and these proposed instruments on SEASAT-A solve this problem. Since the circulation patterns of the constant pressure surfaces become simpler with elevation and turn into the planetary wave patterns at the 500 millibar surface, it follows that defining the complicated 1000 millibar surface correctly and integrating VTPR soundings up to the other reference surfaces will provide a more accurate initial value specification that, say, starting at a higher reference level and integrating both up and down.

WEATHER FORECASTS

Improved weather forecasts on a global basis depend on (1) basic research on the physics of atmospheric, oceanic, continental, and solar interactions; (2) the development of

numerical models of the atmosphere and its interactions with the land, the sea, and the sun's radiation; and (3) the collection of an adequate and correct data base for the initial value specification of the numerical weather forecasting model. SEASAT-A will provide data for item 3 above and produce an improvement in the accuracy and an increase in the range of validity of the forecasts produced by the numerical models described in item 2 above.

Numerical weather prediction models are continuously being refined, improved, and updated so that they can be run on computers of increasingly higher capacity and speed. Nevertheless, they all depend on the accuracy with which the initial values are specified when the computation of the forecasted weather is started.

When random error fields with errors of a size known to exist in the actual initial value data are introduced into a numerical model, the effects of these error fields double each day so that after 4 days they are 16 times as great and the forecasted conditions no longer agree with what actually happened. Reducing the error field in an initial value specification by a factor of two, in effect, makes a three day forecast, using better data, as accurate as a two day forecast using the less correct data.

Random error fields are one way to study the effect of bad data; however, the situation is actually more complicated than this. Over the oceans, especially in the southern hemisphere, entire circulation patterns can be incorrectly specified as to the central pressure of a low and the horizontal extent and spacing of the isobars around the low. These instruments on SEASAT-A can substantially reduce this source of error also. Not only will weather forecasts over the oceans be improved by the data to be obtained but also the forecasts over continental areas such as the western half and the east coast of the United States will be improved in the two to three day time frame.

These proposed instrument systems on SEASAT-A should help to improve forecasts substantially for two to four days for the Northern Hemisphere and should make possible for the first time two to three day forecasts for the Southern Hemisphere.

GLOBAL HEAT TRANSPORTS

Another aspect of this instrumentation on SEASAT-A is that it provides a truly global oceanic data base, when combined with VTPR, for numerical weather prediction. The data base over the continents is, or can much more easily be made, adequate. It will then be possible to model interactions between the two hemispheres. Satellite heat budget studies show that the heat flux that drives the northern hemisphere cyclones in the winter originates from as far south as 30° south and has a magnitude at the equator almost equal to the value at 40° north. The correct description on a day to day basis of this important global feature will be an essential step in fulfilling the stated goal of the National Weather Service of NOAA of providing reliable weather forecasts in the time range from 5 to 10 days. It is however, difficult to say just how much SEASAT-A plus VTPR will contribute toward this goal, since it will probably be necessary to model other aspects of the physics of the weather prediction problem more realistically than at present.

INPUT TO OTHER PROGRAMS

At a time when SEASAT-A will be operational, an extensive worldwide weather observation effort is planned called the First GARP Global Experiment (FGGE) which will be directed toward gathering a detailed climatological data base for the study of the global circulation. The instrumentation on SEASAT-A will supplement the oceanographic data for this experiment and at the same time be complemented by this intensive international effort.

TROPICAL CYCLONES

An example of the value of this system is the potential contribution it can make in obtaining data on the winds and pressures in tropical cyclones wherever they occur. These tropical cyclones are called hurricanes in the North Atlantic, typhoons in the North Pacific, cyclones in the Indian Ocean, and willy-willies in the South Pacific near Australia and New Zealand. They are located by means of a characteristic cloud pattern by the NOAA ATS spacecraft and tracked every 45 minutes or so, as they move across the oceans. With their locations known, ships avoid them almost completely. Thus although their presence is known (recently there were four typhoons in the Pacific at one time), their intensity and potential for damage when moving over land are not known from spacecraft data.

To determine the strength of a hurricane, the United States sends reconnaissance aircraft flights into them on a routine basis whenever they pose a threat to land. These aircraft measure the winds in the hurricane and determine the central pressure. Forecasting the movement of hurricanes is very difficult partly because the atmosphere surrounding them is presently not well enough defined by measurements at a fine enough scale.

However, other nations do not have aircraft reconnaissance flights, and although they know a hurricane is approaching they have no information on its severity. Typhoon winds and rains caused much loss of life and damage in the Philippines just this past year and in 1970 the high wind in a cyclone in the Bay of Bengal caused a storm surge combined with heavy rain that drowned 300,000 people in the Ganges delta region of East Pakistan.

The problem is so acute to a number of nations that a special commission has been organized to attempt to find ways to get better data on the intensity of the surface winds in these storms as they approach populated areas. At the World Meteorological Organization meeting in Tokyo from 2 October 1972 to 7 October 1972, held for the study of the means of acquisition and communication of ocean data, a plea was made by the commissioner for this group for better data on the severity of these storms.

The test version of this instrument (S193) on Skylab has scanned both a hurricane and a tropical storm in a way that may prove to have been the equivalent of having had twenty or twenty-five ships close enough to the storm to define how strong the winds were and how low the central pressure was.

The operational version on SEASAT-A could scan most of the tropical cyclones present over the oceans at least once a day and yield data capable of telling what the winds and pressures were in them. This one accomplishment alone would be an immediate boon to India, Burma, the Philippines, many Pacific Islands (such as Guam), Madagascar, New Zealand, Australia, and Mexico. Just as the adequate warning service of the National Weather Service has greatly reduced the number of lives lost and the property damage due to hurricanes in the United States, similar benefits from this system should be possible for all of the nations just mentioned. As more experience with the system is gained, in a decade or so it might even be possible to dispense with aircraft reconnaissance of the tropical cyclones that threaten the United States.

WAVE FORECASTING

Of all oceanic phenomena, the waves, or storm seas, generated by high winds blowing over large areas of the ocean are the most ever present and rapidly varying patterns. They can grow in height from 15 feet from crest to trough, as an average of the highest waves, to 50 or 55 feet within twelve to eighteen hours as the winds increase. Individual waves more than 80 feet from crest to trough have been measured, and waves over 100 feet high have been estimated.

Storm seas always delay merchant ships as they traverse the oceans; they frequently damage them or their cargoes; and once in a while they cause their loss by capsizing them or breaking them in half or flooding them. Knowing more about the characteristics of the waves on the various shipping routes of world commerce can help improve the design of ships. Better wind, weather, and wave forecasts two to five days into the future, and even further if possible, would make the operation of the more than two hundred million tons of world shipping safer, more efficient, and more economical. Present relatively limited efforts at routing ships save many millions of dollars annually. With improved knowledge of waves and more accurate wave forecasts, additional savings in the merchant shipping industry would be expected from ship routing.

The improved design of commercial shipping is a long term objective that would be enhanced by better data on waves collected on a statistical and climatological basis. The economic benefits would lie in lower insurance costs and increased operating efficiency.

The ability to forecast the waves on the sea surface depends almost solely on the ability to forecast the winds as they vary hour by hour over the oceans. Better weather forecasts as made possible by improved instrumentation systems such as the system on SEASAT-A will permit better wave forecasts. The ability to forecast waves by means of high speed modern computers exists, and improvement in these numerical methods also depends on improved wave observation techniques.

N76 11499

ADVANTAGES OF AN OCEANOGRAPHIC SATELLITE IN THE STUDY OF OCEAN CURRENT SYSTEMS

R. Q. Robe
U.S. Coast Guard Oceanography Unit
Washington, D.C.

Oceanography, conducted from surface ships, has been unable to come to grips with either the space scales or the time scales present in oceanic circulation. Surface oceanography waits on the availability of ship time, waits on favorable weather, and sometimes waits on political considerations. Classical surveys have served well in identifying the major current systems of the world oceans, their location, their speed and direction, and some of their major characteristics such as meandering and eddy production. Surface surveys, by their very nature, are unable to cover the full spectrum of either frequency or wave number space.

Let us first treat the time scales. A cruise attempting to cover a portion of a current system will spend several weeks taking stations. These stations must be treated as synoptic even though no one believes that they are. In areas where the oceanographic regime is changing slowly this type of survey is adequate, but near the edge of major currents, where processes are believed to have a characteristic period of three to five days, the result is a distorted picture which may be either too smooth or too fragmented. In any case a surface survey does not possess either the instantaneous view of a synpotic survey or the statistical view of a time series. The repetition rate for surface surveys is so low that only the grossest seasonal changes can be identified. A statistical analysis is impossible.

On the space scale, the size and form of a phenomenon located by an oceanographic cruise will be a function of the station spacing on the small scale end and the extent of the survey area on the large scale end. Many small eddies, meanders, and oceanic fronts can fall between the 50 to 60 mile station spacing often used in oceanography. Small features can cause an erroneous interpretation of the data analogous to aliasing. At the other end of the scale are the large scale features that hang over the sides of the survey area. It is then possible to see a large eddy or gyre as the meander of a current.

An oceanographic satellite system offers a solution to many of the problems that space and time scales present to the oceanographer working on the surface. On the time scale, repeat coverage could be expected every 36 hours which should be frequent enough to prevent aliasing due to inadequate sampling. Also, the data for the complete globe would be synoptic within 36 hours. Ocean current systems are not greatly affected by the day-night cycle, so the variations in local sun time would present no problems. The length scale difficulties of surface surveys are completely solved by satellite measurements. On the small scale end, the measurements are averaged over the "foot-print" of the sensor used, which smooths over the very small features. The scale of measurements is continuous from this scale up to a global scale, except for areas in the higher latitudes.

SEASAT-A will have two instruments that will be useful in the study of oceanic currents. The first is a scanning radiometer with a temperature resolution of about ±1°C. This instrument would be useful in locating oceanic fronts where the thermal difference is great, such as along the Gulf Stream system where the difference can exceed 10°C. It would be less useful in current systems which

are primarily salinity driven, such as those in the far north. The second instrument of importance in ocean circulation studies is the precision altimeter. With an accuracy of ±10 cm in 10 km the altimeter could give near real time monitoring of the sea surface slopes that drive the major ocean currents. From the surface topography it will then be possible to answer questions about the stability, transport, and scales of these major currents. More minor currents, which are also important to local areas of the world, probably could not be defined by the presently available resolution.

In the study of ocean current systems, surface surveys and satellite measurements must be coordinated to furnish the maximum usable information. Satellites cannot see beneath the surface and ships do not have the ability to cover large areas synoptically and with a high repetition rate. Each should be used with the other in mind, satellites furnishing information on time and length scales and ships providing ground truth and subsurface data.

COMMENTS ON NAVY/NRL REQUIREMENTS FOR SEA SURFACE TEMPERATURE AND SURFACE WIND MEASUREMENTS ON SEASAT-A

R. E. Ruskin and R. K. Jeck, Jr.
Naval Research Laboratory
Washington, D.C.

BACKGROUND INFORMATION

The Atmospheric Physics Branch at the Naval Research Laboratory (NRL) is a potential user of SEASAT-A data for application to an ongoing Marine Fog Studies project. This project is of importance to the Navy because of the potential for improving marine fog prediction capabilities, particularly in fleet operations. It is envisioned that, at a future time, satellite data such as that from SEASAT and the Defense Meteorological Satellite Program (DMSP) (formerly DAPP) may be utilized in nearly real time by ships at sea for operational fog reconnaissance and forecasting.

For such an application the most important data which can be supplied by instrumentation available for use on SEASAT-A are measurements of Sea Surface Temperature (SST) and its gradients, and of surface winds. Based on recent NRL experience with SST data from NOAA-2 and DMSP satellites in conjunction with measurements at sea, the requirements of the current marine fog studies and of the future Navy fleet operational fog prediction program emphasize a need for SEASAT instrumentation including the following:

1. Some form of C-band microwave radiometer capability will be necessary if SEASAT is to have any significant advantage over existing satellites for the purpose of SST measurement;

2. The preferred payload would include a scanning antenna with a 40-km Instantaneous Field of View (IFOV) for the C-band channel; but an acceptable compromise would be a modified Nimbus-G package with a scanning, 80-cm-diameter antenna and an IFOV of 100 km for the C-band channel. A second compromise would provide a fixed C-band antenna with a 40-km IFOV.

3. A narrow-band and high resolution IR scanning radiometer is required in order to provide SST with 0.5 to 4 n. mi. resolution and improved accuracy in the cloud-free areas; accuracy requirements for the combination of microwave and IR are ± 0.5°C relative and ± 1.5°C absolute.

4. Capability for measuring surface winds should have minimum requirements of 3-50 m/sec in range, ±2 m/sec or ±10% in accuracy, and 50-100 km spatial resolution.

We elaborate on the reasoning behind these requirements in the following sections.

THE SCANNING MULTIFREQUENCY MICROWAVE RADIOMETER (SMMR): REQUIREMENT FOR THE C-BAND (5-8 GHz) CHANNEL

From briefings given at recent SEASAT-A users conferences, we understand that there is a distinct possibility that the SMMR to be flown on SEASAT-A will be a copy of the Nimbus-G prototype having four microwave channels in the frequency range between 10 and 36 GHz. However, if the SMMR is to be useful for fog studies via SST measurements, then a fifth (C-band) channel is necessary, since 5-8 GHz is the only proposed frequency band minimally influenced by factors other than temperature. In addition, without the C-band channel the SMMR would be unable to see through even light cloud cover and it

would thus lose its main advantage over any Visible/Infrared (V/IR) imaging radiometer. This advantage is important for geographical regions which have a high frequency and/or persistence of cloud cover.

Since present technology cannot provide a satellite-mounted SMMR with IFOV and signal/noise ratios that simultaneously approach those of optical radiometers, the V/IR imaging radiometer will still be needed as the primary sensor for studying medium- to small-scale thermal features on the sea surface. But the potential for seeing through clouds and for providing both substitute SST truth data and atmospheric water vapor correction for the V/IR imaging radiometer makes the C-band equipped SMMR a valuable complementary instrument. Since the V/IR imaging radiometer to be flown on SEASAT-A will probably be a simple two-channel instrument without means for correcting SST data for atmospheric water vapor or cloud effects, the C-band and other SMMR data will be essential, even for cloudless areas, if SEASAT-A is to provide SST data useful for fog studies.

We understand that there are three feasible methods for incorporating the C-band channel into the SEASAT-A payload. The most beneficial configuration for SST purposes is a 2-meter-diameter scanning antenna to provide a 40-km IFOV over the entire sea surface. The method making use of the multifrequency feed on the standard, 80-cm-diameter scanning antenna of the Nimbus-G prototype SMMR is less desirable because of the wide (100 km) IFOV for the C-band channel, but it is an acceptable compromise vis-à-vis no C-band at all, since it would still provide the important capability for measuring SST through light cloud cover. An alternate proposal for mounting a separate, nonscanning, 2-m diameter, C-band antenna on the satellite would result in improved C-band IFOV again, but this benefit would be offset by lack of ground coverage due to the fixed, nadir-looking antenna.

An example of the relative potential utility of each of these three methods comes from a situation encountered by the USNS Hayes on a recent scientific cruise in the east-central Pacific. During this cruise SST and SST gradients indicated by IR data from DMSP satellites were compared with surface truth data obtained by the Hayes. Preliminary analysis finds the DMSP data underestimating SST by 16°C in one case and overestimating an SST gradient by a factor of three in another case involving a 60-km wide, cold-water region. Had these data come from a SEASAT-type of satellite, the error in SST gradient would certainly have been correctable if C-band data from a scanning 2-m (40-km IFOV) were available. It would probably have been at least partially correctable by use of C-band data from a scanning 80-cm (100-km IFOV) antenna, but probably would not have been correctable in this case by C-band data from a fixed, nadir-looking antenna.

THE VISIBLE/INFRARED IMAGING RADIOMETER: REQUIREMENT FOR AT LEAST MODERATE RESOLUTION

As was mentioned earlier, the relatively poor (large) IFOV of existing C-band capabilities means that the V/IR imaging radiometer will still be required not as an auxiliary instrument but as *the primary sensor* for studying medium- and small-scale thermal features on the sea surface. For this application a picture resolution of 2 n. mi. in the visible channel and 4 n. mi. in the IR is satisfactory. Inclusion of a vertical-temperature-profile radiometer (VTPR) or other water-vapor-correction channels in the IR would be desirable but not necessary if choices are limited to minimum requirements.

N76 11501

ON THE REMOTE SENSING OF DIRECTIONAL WAVE SPECTRA AND SURFACE WINDS

O. H. Shemdin
Coastal and Oceanographic Engineering Laboratory
University of Florida
Gainesville, Florida

INTRODUCTION

This paper is restricted in scope to the problem of remotely sensing wind and directional wave spectra by active microwave systems. Knowledge of the wave climate on a global scale is important to shipping and other deep ocean operations. In addition, the local wave climate on the continental shelf and in the nearshore areas is detrimental to the coastal and nearshore operations. It is estimated that 90% of man's ocean activity is in water depths shallower than 30 meters and in these depths wave activity represents the single most important environmental factor affecting offshore planning and design. The determination of the wave climate by remote sensing methods from satellites will offer invaluable support to ongoing activities and future ocean explorations. It is apparent that optimum use of satellite data will be in conjunction with global and local wave and wind forecasting schemes such as those in use at Fleet Numerical Weather Central. The satellite input will be initially most valuable in establishing the validity of existing numerical models which can then be used for operational purposes.

TECHNICAL CONSIDERATIONS

Initial investigations of ocean waves by active microwave systems were aimed at establishing a relationship between radar backscatter return and wind speed. The possible use of radar as a remote anemometer offers many advantages over existing onsite anemometers in terms of efficiency and spatial coverage. Recent laboratory and aircraft experiments indicate a positive relationship between wind speed and radar backscatter return. The available data (*Pierson and Moore,* 1972) also exhibit unacceptable scatter about the mean (as high as 100%).

Laboratory studies by *Wright and Keller* (1971) indicate that Bragg scattering dominates radar return signals for angles greater than 10 degrees from nadir. The primary return is from capillary waves. The dynamics of capillary waves, therefore, assume central importance in understanding radar return.

Capillary waves are sensitive to wind forcing, local currents, orbital velocities of long gravity waves, changes in surface tension due to slicks induced by oil spills or biological activity. Laboratory experiments by *Shemdin et al.* (1972) (Figure 1) indicate a linear relationship exists between capillary wave slope energy and wind speed for each frequency. A saturation level is achieved at a certain wind speed beyond which the slope energy remains constant. Higher frequencies achieve saturation at higher wind speeds. The same study (Figure 2) also indicates the influence of long waves on capillary waves at various wind speeds. These results provide an understanding of the scatter evidenced in relating wind speed to radar backscatter. Indeed, wind speed is only one of the variables that affect capillary waves which in turn determine the magnitude of the backscatter.

The Coherent Imaging Radar has the capability of detecting long gravity waves and directions primarily because capillary waves vary in intensity along the profile of long waves. The variation is induced directly or

indirectly by the orbital velocities of the long waves. The interaction between capillary waves and long gravity waves in non-linear and a complete understanding of the process is under investigation by theoreticians and experimentalists alike. At present it is not evident how one may obtain heights of the long gravity waves from variations of the radar imager return from various phase positions along the profiles of the long waves. The remote determination of the directional wave spectra is of central importance to users involved in design and protection in the coastal and offshore areas.

FUNCTIONAL REQUIREMENTS

Different functional requirements are stipulated for global wind and wave climatology and for coastal and shallow water climatology. The wave and wind requirements are summarized in Table I.

In shallow coastal waters the land/water boundary and offshore bottom configurations produce significant changes in both wave height and direction. An adequate understanding of these changes can make it possible to translate the wave climatology from the deep to shallow water.

INFORMATION NEEDS

Considerable evidence exists on the direct relationship between wind speed and radar cross-section which is fundamental to the use of the scatterometer as a remote anemometer. The scatter in the data, which can be as much as 100%, suggests that ongoing studies must be continued.

As indicated before, the dynamics of capillary waves play a central role in radar return from the ocean surface at angles greater than 10° nadir. Field measurements of capillary waves hardly exist at the present time and must be developed. Recent laboratory measurements of capillary waves by *Shemdin et al.* (1972) verify the existence of strong interactions between capillary waves and long gravity waves. *Wright and Keller* (1974) more recently placed an x-band doppler radar over the same laboratory facility and found that the return from the water surface is strongly modulated by the long gravity waves. Sufficient evidence is already in hand suggesting that radar return is not only governed by wind but by all physical and dynamical factors which control the generation and decay of capillary waves.

The imaging radar's detection of long gravity waves is another manifestation of the above observations. While at present the wave length and direction can be obtained from the imaging radar it is not yet possible to obtain wave height. Research into the dynamics of capillary wave modulation by long waves and the effect on surface backscatter may be useful in relating heights of long gravity waves to the modulation of the capillary wave backscatter over the wave profile. Photographic methods exist where directional wave number spectra of long waves can be obtained. The aim must be to develop the methodology where the imaging radar information can be treated as an all weather photograph from which directional wave number spectra can be extracted.

The following experiments are recommended:

1) Continue laboratory studies of capillary waves in conjunction with doppler radar mounted over wave tanks.

2) Develop instrumentation to study ground truth capillary waves in the ocean in conjunction with doppler radars mounted on platforms nearby.

3) Investigate the return form imaging radars and scatterometers in flight over field stations where capillary and gravity wave ground truth information is available.

4) The careful monitoring of wind speed, surface tension, currents, and aerodynamic stability of the boundary layer must be provided throughout the above investigations.

5) Simultaneous aircraft and satellite measurements need to be correlated for calibration.

ANTICIPATED RESULTS AND POTENTIAL BENEFITS

It is now known that without today's weather satellites the accuracy of weather predictions would be grossly inferior to those being obtained with the use of satellites. The analogy between weather and wave climatology is valid. The potential benefits of having wind and waves from a satellite on a global scale are immeasurable. The greatest potential in using this information would be through a combined effort which uses numerical forecasting and hindcasting schemes such as those used by Fleet Numerical Weather Central. The latter operation already relies on satellite information for determining global pressure and wind patterns which are used to forecast waves by conventional wave forecasting methods. The supplemental addition of direct wind and wave measurements from satellites would no doubt upgrade the accuracy of existing wave forecasting schemes by an order of magnitude. The existing schemes often have errors as high as 100%. The increment of information to be made available by SEASAT-A will no doubt make existing schemes grossly inferior. The potential benefits will be primarily to shipping, offshore exploration of minerals, oil, and power generation. Disaster prediction and minimization of property damage will no doubt be accrued.

CONCLUSION

The benefits of SEASAT-A will be immeasurable even if it could only provide wind and wave information on a global scale. The benefits can be optimized through a combination of research and operation coupled with numerical modeling of wind and waves. Maximum use of the instruments aboard SEASAT-A will be achieved in conjunction with a comprehensive program of research on both laboratory and field levels. Use of aircraft is seen necessary to calibrate the instruments in flight. Detailed ground truth measurements must include capillary waves.

TABLE I.

	Surface Wind	Waves
Deep water (global)	Velocity = 2-50 m/sec	Wave length = 50-500 m; 25 m resolution
	Direction = 0-360°; ±20° FOV = 20 x 20 km Sample Intervals = 250 km	Direction = 0-360°; ± 10° Height = 0.5-30 m; 0.5 m or ± 10% FOV = 20 x 20 km Sample Intervals = 250 km
Shallow water (local)	Velocity = 2-50 m/sec	Wave length = 50-500 m; 25 m resolution
	Direction = 0-360°; ± 20° FOV = 3 x 3 km Sample Intervals = 50 km	Direction = 0-360°; ± 10° Height = 0.5-30 m; 0.5 or ± 10% FOV = 3 x 3 km Sample Intervals = 250 km

REFERENCES

Pierson, W. J., and R. K. Moore, "A Proof of Concept . . .," *Technical Conference on the Means of Acquisition and Communications of Ocean Data*, Tokyo, 1972.

Shemdin, O. H., Lai, R. J., Reece, A. and Tober, G., "Laboratory Investigations of Whitecaps, Spray and Capillary Waves," *Coastal and Oceanographic Engineering Laboratory, Technical Report No. 11*, 1972.

Stillwell, D., "Directional Energy Spectra of the Sea from Photographs," *J. Geophys. Res., 74*, 1969.

Wright, J. W. and W. C. Keller, "Doppler Spectra in Microwave Scattering from Wind Waves," *Phys. Fluids, 14*, 1971.

Wright, J. W., and W. C. Keller, Private Communication, 1974.

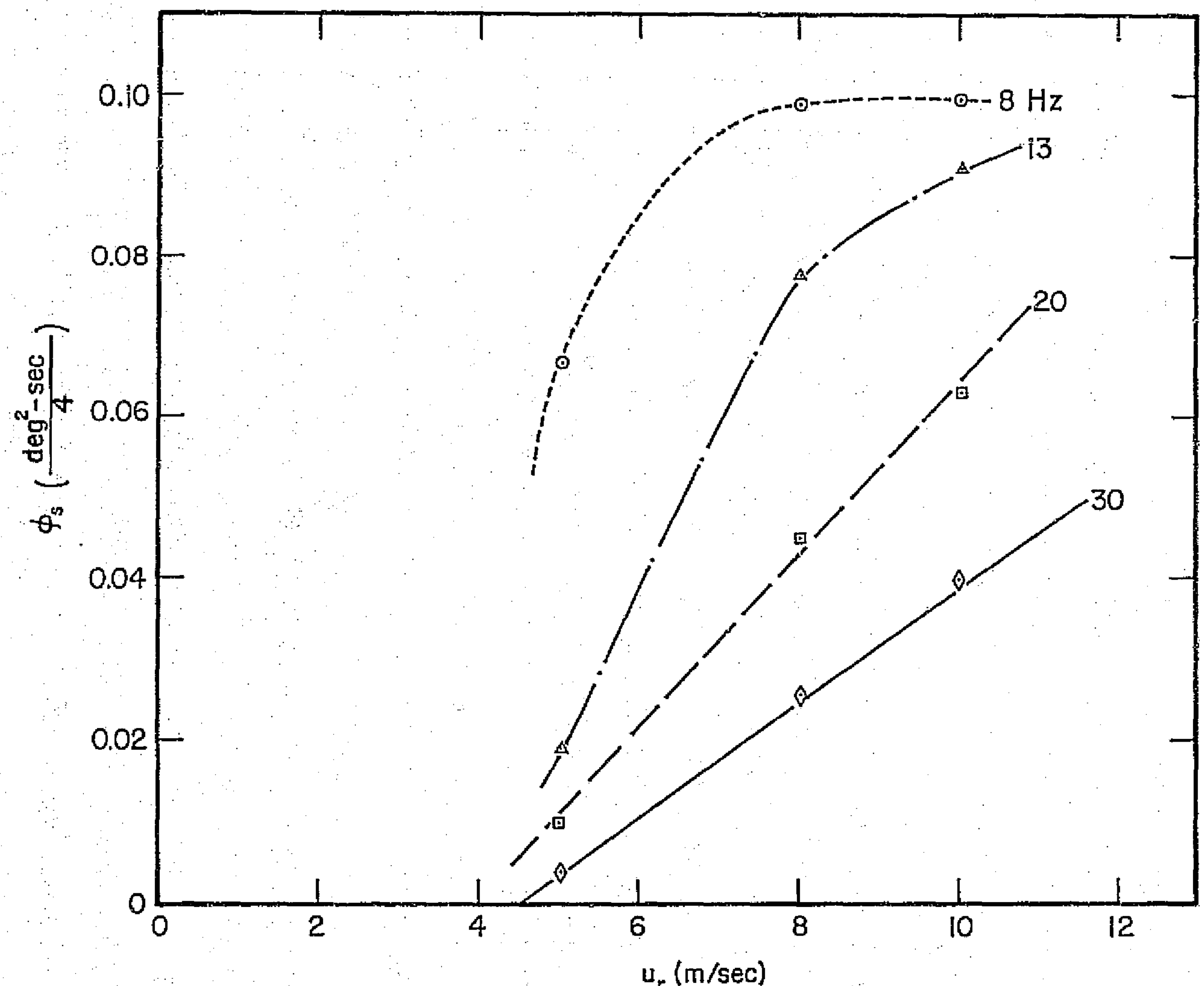


Figure 1.–Wind dependence of slope spectral values at different frequencies. ⊙ – *8 Hz;* △ – *13 Hz;* ⊡ – *20 Hz;* ◇ – *30 Hz.*

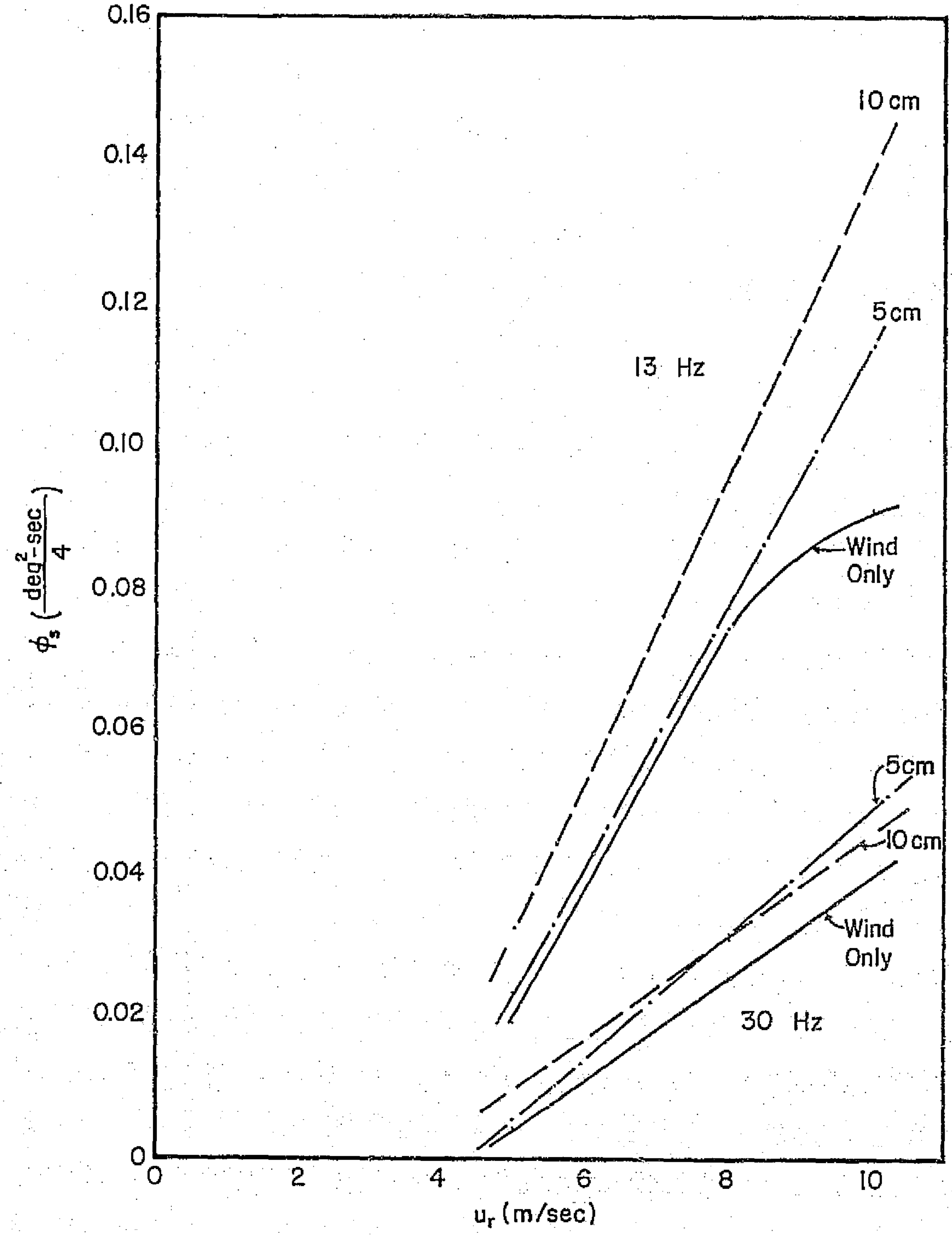


Figure 2.–Dependence of slope spectral values at 13 and 30 HZ on mechanically generated waves.–wind waves only; – • – with 5.0 cm swell height; - - - - with 10.0 cm swell height.

N76 11502

MICROWAVE MEASUREMENT OF SEA SURFACE TEMPERATURE

John W. Sherman III and P. Krishna Rao
National Environmental Satellite Service
National Oceanic and Atmospheric Administration
Washington, D.C.

INTRODUCTION

The microwave region offers the potential for measuring sea surface temperature from platforms such as aircraft or satellites, remotely located above the ocean surface. Remote sensing, as these techniques are designated, of ocean variables from earth orbiting satellites have attracted the attention of marine scientists for the last decade (*Ewing*, 1965). Experiments conducted using instruments aboard satellites have shown specifically that it is possible to measure sea surface temperatures (SST) under relatively cloud free conditions using the infrared (IR) portion of the electromagnetic spectrum. The choice of appropriate frequencies for the SEASAT-A spacecraft will permit current research to be extended to evaluate the use of microwave radiometers to measure SST.

The objective of this paper is to emphasize the research to be accomplished in microwave radiometry in order that global determination of SST may be accomplished and to discuss certain features of microwave observations which set them apart from the infrared measurements of radiative temperature. This paper addresses the interaction of microwave energy with the ocean surface, the proposed SEASAT instrument, the measurement of SST, including microwave techniques, and research SST studies potentially available using SEASAT-A.

THE INTERACTION OF MICROWAVE ENERGY WITH THE OCEAN SURFACE

This section is limited to those properties of microwave energy that influence the measurement of SST. It is recognized that microwave energy is significantly less affected by atmospheric conditions than infrared energy. However, the ocean is nearly a blackbody at infrared frequencies, but at microwave frequencies has an emissivity which ranges from 0.28 at 1 GHz to 0.41 at 20 GHz (20°C, salinity 35 ppt) for zero incidence angle of observation. Polarization also affects the emissivity. Figures 1 and 2 show the influence of angle, and frequency on the emissivity as it influences the observed brightness temperature of ocean water at 20°C.[1] Figure 1 is for vertically polarization and Figure 2 is for horizontal polarization.

The influence of physical temperature on the observed brightness temperature (due to the dependence of emissivity on physical temperature) is shown in Figure 3. The range of physical temperatures in this figure is the total range of ocean physical temperature. Two regions appear best suited for measurement of SST. First, the UHF region at about 500-600 MHz; and second, the C-band region or about 4-6 GHz. From the standpoint of an aerospace system, the C-band region is preferred because spatial resolution is determined by antenna diameter as measured in wavelengths. Thus, for a given spatial resolution, the C-band antenna can be nearly an order of magnitude smaller than for a UHF system. Further, C-band is also preferred from the standpoint that the brightness temperature is essentially independent of salinity at 5-6 GHz

[1]The data in Figures 1-5 are provided through the courtesy of Dr. James Hollinger of the Naval Research Laboratory (*Hollinger*, 1973).

but does have a slight dependency on salinity in the UHF region for typical ocean salinities (between 33 to 38 ppt). Figure 4 shows this dependence at an ocean physical temperature of 20°C. Thus, it appears that the 5-6 GHz region of the microwave spectrum is best suited for the measurement of SST. However, this statement assumes that atmospheric effects are fully compensated for in the measurement. If not, the frequency should be somewhat lower as will be discussed subsequently in the section on Sea Surface Temperature Measurement.

The actual surface of the ocean involved in the interaction of electromagnetic energy depends primarily on the skin-depth, i.e., the distance in the surface in which the energy is reduced to $^1/\epsilon$ of the value incident at the surface. In the IR region this skin-depth is measured in micrometers. In the microwave region the depth is a matter of centimeters and is frequency dependent. Figure 5 shows this relationship at two physical temperatures. The skin-depths at 20°C are 3.4, 2.8, 2.3, and 1.9 cm at 4, 5, 6, and 7 GHz, respectively. Thus, the microwave observed temperature will more closely represent the bulk ocean temperature than the radiometric temperature measured by IR radiometers, especially when surface winds are light with little surface mixing.

The nearly all-weather measuring feature appears as the major advantage for the microwave approach over existing IR techniques. However, the physical properties of ocean water may negate some of the advantages gained by using microwave energy to penetrate the atmosphere. Since the emissivity of ocean water is about 0.36 in the C-band region, the reflectivity is 0.64. Hence, the surface of the ocean is more nearly a reflector than a radiator. Fortunately, the sky is relatively "cold" in the microwave region due to its own low emissivity, but as increased water and water vapor are introduced into the atmosphere the emissivity increases and it becomes warmer. The net result is that the atmosphere will affect the microwave observation of SST in two ways. First, an attenuation of the direct signal received from the surface (as is the case for IR observations); and second, the reflected sky illumination from the surface (the IR signal is nearly totally radiated so that essentially no sky component is reflected). Further, the sky illumination is an integrated signal from all angles and cannot necessarily be compensated for by measurement of atmospheric effects along the line-of-sight from the microwave radiometer to the ocean surface. The reflection of sky temperature may well be the major limiting factor in the measurement of SST by microwave techniques.

This section has dealt only with the specific properties of the ocean that influence the measurement of SST. It must be recognized that wave slope/height (sea state) and spray/foam/white water/capillary structure (surface wind) will alter microwave brightness temperature. In order to make SST microwave observations, these features must also be compensated for using corrective techniques which include multiple frequency observations and/or active microwave observations.

THE SEASAT MICROWAVE RADIOMETER SYSTEM

The instrument that is under consideration for SEASAT-A is a five frequency, dual polarization, scanning microwave radiometer operating at about 5, 10, 18, 22 and 37 GHz. The X-band (10 GHz) may be deleted from the system. The spatial resolution of the instrument is to be about 100 km at the lowest frequency (5 GHz, C-band) and will have a swath width of about 870 km. The scan angle may be fixed at about 55° angle of incidence (a conical scan) or may scan orthogonal to the flight track. The C-band component of the system satisfies the minimum requirements for SST observation of the ocean surface, if the instrument meets the

stated absolute accuracy of ±1.5°C and relative sensitivity of ±1.5°C.

Global coverage will be obtained approximately every 36 hours between ±72° latitude. The convolution of data using algorithms yet to be specified will permit the observation and measurement of surface wind fields (X-band data), the amount of liquid and water vapor content in the intervening atmosphere (18 and 22 GHz or K-band), and limited data on the extent of sea ice (37 GHz or K_a-band).

SEA SURFACE TEMPERATURE MEASUREMENT

SST distribution is an important parameter in the geophysical and marine sciences. Ships, historically, have been the only source of global operational information on ocean variables, particularly SST. Today these surface observations continue to provide a significant amount of SST data, primarily located along the shipping lanes. *James and Fox* (1972) have shown that the current ship data coverage is too sparse. For example, in an entire year the total number of observations collected were about 16,000 with approximately 37 percent between 0° to 25° latitude, 52 percent from 25° to 50° latitude and the remaining 11 percent above 50° latitude. Further, it has been shown (*Fotheringham*, 1972) that with the instruments currently available for ship board measurements, it is possible to measure the bulk temperature at the ocean surface with an absolute accuracy of ±0.3°C.

At less frequent intervals and over specific areas of the ocean, aircraft radiometric observations are available and meso-scale SST analysis obtained. Accuracy of the aircraft measurement of radiative temperature are on the order of ±0.5°C for low altitude flights, with relative measurement approaching 0.1°C or better. Not infrequently, when rough weather prevails over any oceanic region, both ships and aircraft typically avoid these areas and limit most SST observations to non-hazardous environments. Satellite measurements, and particularly the microwave observations, may become the only source of data.

SST measurements from satellite IR observations have been discussed in detail in many studies (*Allison and Kennedy*, 1967; *Sherman*, 1969; *Smith et al.*, 1970; *Rao et al.*, 1972; *Shenk and Solomonson*, 1972). Most of the data used in these studies were from either the 4 or 11 micrometer "atmospheric window" region of the electromagnetic spectrum. It is appropriate to briefly review the status of such measurements. By applying the appropriate atmospheric attenuation corrections and statistical analyses of the data, SST can be derived for relatively cloud free areas.

For areas as large as 100 km square, a comparison between satellite derived data and conventional data shows that the root-mean-square difference is 1.5-2.0°C (*Smith et al.*, 1970; *Rao et al.*, 1972; *Smith and Rao*, 1971). In many instances the satellite temperatures were lower than the ship observations by 0.5-1.0°C. Part of the systematically lower temperature can be attributed to a surface slightly cooler (due to radiative cooling) as compared to the bulk temperature, and part due to a cooler, attenuating atmosphere. The root-mean-square difference is also due to satellite sensor system noise uncertainties in sensor calibration, errors of the SST observation, ground station receiver noise, rounding-off errors in analog-to-digital conversion, and atmospheric noise.

By using multispectral methods, errors due to cloud contamination can be minimized (*Smith and Rao*, 1971; *Shenk and Solomonson*, 1972). Further, a better estimate of the magnitude of the atmospheric attenuation correction can be obtained. These multispectral techniques, when incorporated in such instruments as the Advanced Very High Resolution Radiometer (AVHRR) planned for TIROS-N, will provide an absolute accuracy

of ±1.0°C and a relative accuracy of ±0.5°C over a 10-km square area.

These accuracies require cloud free conditions. The microwave radiometer for SST will be multispectral, just as AVHRR, for the same basic reason, namely, atmospheric correction, as well as corrections for sea surface features. It has been indicated that it is possible, in the absence of foam, to predict the sea brightness temperature, as related to the SST, to within ±1.0°C (*Porter and Wentz,* 1972). At nadir observation angles the highest slope of apparent microwave temperature to physical temperature is 0.5 and occurs at 5.4 GHz (*Paris*, 1969, and *Hollinger*, 1973). Thus, a brightness temperature measured to ±1.0°C corresponds to an SST absolute measurement of no better than ±2.0°C assuming no other variables or errors.[2]

It is important to summarize the measurement of SST when the properties of the ocean surface are combined with the effects due to the atmosphere. In order to do this the effects of the atmosphere on SST observations are assessed assuming that a single frequency observation is made. Figure 6 shows the microwave measured nadir SST uncertainty compared to clear conditions as a function of frequency due to an atmosphere that is cloudy, contains moderate rain or has heavy rain (*Porter and Wentz,* 1971). Figure 7 is similar for a 60° angle of incidence. The advantages of a 5 GHz SST observation are diminished when the increased atmospheric effects are considered. If a single frequency is used then the best frequency is 3.0±0.5 GHz (*Porter and Wentz,* 1971). The single frequency assessment also implies the importance of atmospheric corrections in the SST measurement using other frequencies. Only if these corrections are made by use of the other SEASAT passive microwave channels will the best SST observational frequency be 5-6 GHz.

It is expected then that in the 1978 timeframe, the SST accuracy will be on the order of ±0.3, ±1.0 and ±2.0°C for bulk, radiative, and microwave measurements respectively. The capability to provide accurate surface data at a point will not be a limiting factor, but spatial scales will be difficult to achieve. Radiative temperature measurements from space at high spatial resolutions (1 km from AVHRR aboard the NOAA series of polar satellites) will permit an assessment of the gradient field in a specific region chosen for analysis, and repeated observations at lower spatial resolution (GOES[3] 10 km IR data) will provide data up to 40 or 50 times per day on the meteorological conditions of the region. Once the capability of the SEASAT-A microwave system is established for a number of meteorological situations, large region SST maps will permit investigations of SST phenomena in regions of persistent cloud cover (Intertopical Convergence Zone) and possibly the marine storm environment.

The ±2.0°C at 100 km sampling will be marginal for many marine applications. However, it is comparable to the first IR radiometers deployed in space systems. Further, there is a considerable advantage in providing the planned scan mode to the microwave radiometer, that extends the initial experiments begun on Comos 243, which in 1968 carried four non-scanning radiometers operating at 3.5, 8.8, 22.2 and 37 GHz (*Tomiyasu,* 1974). The anticipated capability of the SEASAT-A SST radiometer will permit experimental evaluation for making the necessary surface and atmospheric corrections to measure sea surface temperature.

SCIENTIFIC STUDIES OF SEASAT-A DATA FOR SST

This section identifies some of the unique scientific SST studies that the C-band fre-

[2] SEASAT-A expects ±1.5°C, but pragmatically speaking, ±2.0°C is believed more realistic.

[3] GOES–Geostationary Operational Environmental Satellite to be operated by NOAA.

quency on SEASAT-A affords to investigators. Eight general areas have been suggested which include the development of algorithms; comparison of microwave, radiometric and bulk SST; determination of the best observation angles; influence of solar brightness temperature; studies of polarization related to SST; investigation of large scale ocean fronts; studies of major storms over the ocean; and support of major, ocean related programs. While the areas are identified separately, they are somewhat interdependent and to a certain extent require successive successful accomplishment. Limited results will be obtained if algorithms cannot separate the variables influencing the C-band signal. In no way is this section intended to be an experiment design or outline, but only to establish topics of importance for research.

Development of Algorithms

For purposes of SST measurement, the development of successful algorithms requires scientific experimentation for the evaluation of atmospheric temperature, emission and absorption, as well as surface temperature, emission and reflection. As discussed in the second section, the microwave brightness temperature is influenced by not only the line-of-sight atmospheric factors, but the total sky effective temperature reflected from the ocean surface. Thus, the atmospheric and surface features are not as straight-forward with passive observations as with active microwave measurements where a controlled, range-gated signal is available.

Comparison of Microwave, Radiometric, and Bulk SST

The research for this comparison will require the analysis of SST data from other satellite systems (the Geostationary Operational Environmental Satellite—GOES—is particularly suited) which can be integrated over large areas comparable to the spatial resolution of SEASAT-A. The bulk temperatures will be difficult to compare directly to the SEASAT-A data except in the major shipping lanes or in large-scale ocean experiments such as GATE at the present time or the First Global GARP Experiment (FGGE) planned for the 1978 timeframe. It is only through these types of comparisons that both an understanding and evaluation of the different types of SST can be accomplished.

Selection of the Best Observation Angle

The microwave radiometer system on SEASAT-A will scan ±25° from nadir, orthogonal to the flight track or will be a conical scan at a fixed angle of incidence. However, the region from 40° to 60° angle of incidence at the surface is an important area for research. The general emission characteristics at 5 GHz for the ocean under the influence of a surface wind are shown in Figure 8 (*Porter and Wentz*, 1972). There is a cross-over point between 40° and 50° wherein the vertical polarization brightness temperature is independent of wind effects. The reason is primarily due to the fact that foam emissivity decreases with angle out to about 60° which negates the increase in emissivity as shown in Figure 1. The actual cross-over point is not fixed, but depends on other environmental variables.

For operational purposes, the ±25° scan angle is necessary. For purposes of scientific investigation, the experimental program can be expanded if the antenna configuration is pivoted away from vertical to allow a scan of say 0° to 50° or 25° ±25°.[4] This is believed to be a necessary consideration to determine the best angle for SST measurement.

Influence of Solar Brightness Temperature

The solar brightness temperature is about 25,000°K in the C-band portion of the

[4]It may be better to scan from 10° to 60° because of data uncertainties related to foam effects.

spectrum. The non-sunsynchronous orbit of SEASAT-A will at times cause erroneous results when the sun is specularly reflected into the antenna system. In general, such errors will be obvious. However, basic experiments can be performed (assuming sufficient dynamic range in the receiver) using the sun as a source to check surface scattering models, just as glitter patterns obtained from visible region space sensors have been used to infer surface roughness conditions (*Strong and Ruff*, 1970).

Polarization Properties Related to SST

The general effects of polarization have not been investigated for many of the oceanic variables, except surface windfield phenomena. The atmospheric emission (or absorption) is relatively unpolarized in the microwave region while the surface emission is strongly polarized in the C-X band region (away from nadir). *Hollinger* (1971) has proposed that the percent polarization be used as means of measuring surface winds. Such a technique has the inherent advantage that atmospheric attenuation, etc., do not influence the measurement, as long as the influencing variable is not polarized. Experimental C-band studies of temperature/polarization effects are needed beginning with initial laboratory measurements before 1978.

Large Scale Ocean Fronts

A spatial resolution approaching 25-40 km would enhance the ability to monitor ocean frontal systems over the 100 km SEASAT-A configuration. However, large frontal systems can be mapped and tracked with the planned system provided the relative SST capability approaches ±1.0°C or better.[5] It needs to be emphasized that frontal systems do not require high absolute accuracy, only good relative sensitivity. This is not the case historically, where ships required long observation periods (weeks) to map such fronts and the absolute measurement was the essential element. A space system which maintains relative capability over periods as short as tens of minutes can map such ocean frontal systems. SEASAT-A, as planned, should have relative capability which exceeds this time duration.

Studies of Major Storm Systems

The mapping of SST characteristics in conjunction with major storms, in particular hurricanes, potentially can assist in predicting the movement. It cannot be determined at this juncture if 100 km will permit useful monitoring for this application. Again, it appears that relative SST may suffice for studying the relationship between hurricane movement and SST provided absolute measurements are available from other sources.

Support of Major Ocean Related Programs

Two major programs which offer mutual support to SEASAT-A are the First Global GARP Experiment (FGGE) and the Northern Pacific Experiment (NORPAX). Both include the study of sea-air interactions and can benefit the SEASAT-A effort both in the scientific and operational demonstration programs. SEASAT-A potentially will provide synoptic data to these programs.

Other major national efforts such as STORMFURY will be used in initial aircraft studies. Presently, aircraft missions are tentatively planned during the summers of 1976 and 1977. The next evolution of the STORMFURY effort beyond 1977 is not presently defined, but SEASAT-A can assist in monitoring of major storns.

RECOMMENDATIONS

In reviewing the SEASAT-A microwave radiometer for scientific studies related to sea surface temperature measurement, the limited swath width appears to negate certain research studies at angles greater than about 30° from nadir. It is recognized that symmetrical scans are best for operational experiments, but it is

[5]SEASAT-A expects ±0.5°C relative accuracy.

believed that an experimental scan mode will improve the overall knowledge gained. It is recommended that a mode of scan be incorporated which permits data to be collected from nadir up to 55° - 60° from nadir, even if an asymmetrical scan is necessary.

REFERENCES

Allison, L. J., and Kennedy, J., 1967, *NASA Tech. Rep. D-4078.*

Ewing, G. C., Editor, 1965, Oceanography From Space, Woods Hole Oceanographic Institution, Woods Hole, Mass.; Ref. No. 65-10.

Fotheringham, R. R., 1972, *WMO Report on Marine Science Affairs, Report No. 7.*

Hollinger, J. P., 1971, "Passive Microwave Measurements of Sea Surface Roughness," IEEE Trans. Geoscience Electronics, Vol. GE-9, pp. 165-169.

Hollinger, J. P., 1973, "Microwave Properties of a Calm Sea," Naval Research Laboratory, Report No. 7110-2.

James, R. W., and Fox, P. T., 1972, *WMO Report on Marine Science Affairs, Report No. 5.*

Paris, J. F., 1969, "Microwave Radiometry and Its Application to Marine Meteorology and Oceanography," Dept. of Oceanography, Texas A&M University, Ref. 69-IT.

Porter, R. A., and Wentz, III, F. J., 1971, "Microwave Radiometric Study of Ocean Surface Characteristics," *Radiometric Technology, Inc. Contract 1-35140.*

Porter, R. A., and Wentz, III, F. J., 1972, "Research To Develop a Microwave Radiometric Ocean Temperature Sensing Technique," *Radiometric Technology, Inc. Contract 2-35309.*

Rao, P. K., Smith, W. L., and Koffler, R., 1972, *Monthly Weather Review,* Vol. 100.

Shenk, W. E., and Solomonson, V. V., 1972, *Journal of Physical Oceanography,* Vol. 2.

Sherman, III, J. W., 1969, "Passive Microwave Sensors for Satellites," Proc. 6th Int Symp. Remote Sensing of Environment, Vol. 2, pp. 651-669.

Smith, W. L., and Rao, P. K., 1971, "The Determination of Surface Temperature from Satellite Window Radiation Measurements," Presented at the Fifth Symposium on Temperature, Washington, D.C., June 21-24, Published by Instrument Society of America, 400 Stanwix Street, Pittsburgh, Pa., pp. 2251-2257.

Smith, W. L., Rao, P. K., Koffler, R., and Curtis, W. R., 1970, *Monthly Weather Review,* Vol. 98.

Strong, A. E., and Ruff, I. S., 1970, Utilizing Satellite-Observed Solar Reflections, 4th Annual Earth Resources Survey Program Review NASA/JSC.

Tomiyasu, K., 1974, "Remote Sensing of the Earth by Microwaves," Proceedings of the IEEE, pp. 86-92.

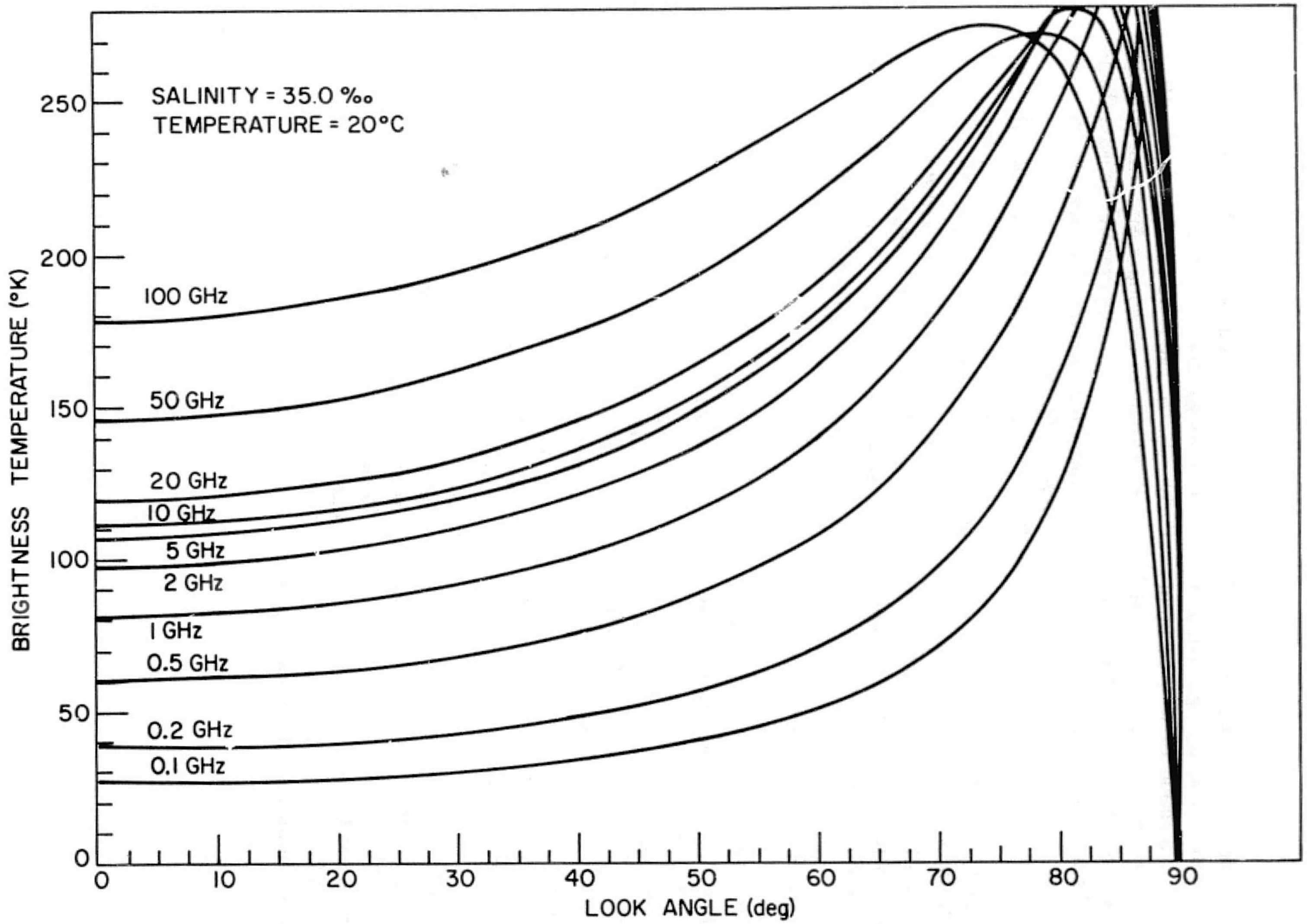


Figure 1.–Vertically polarized microwave brightness temperature of the ocean surface.

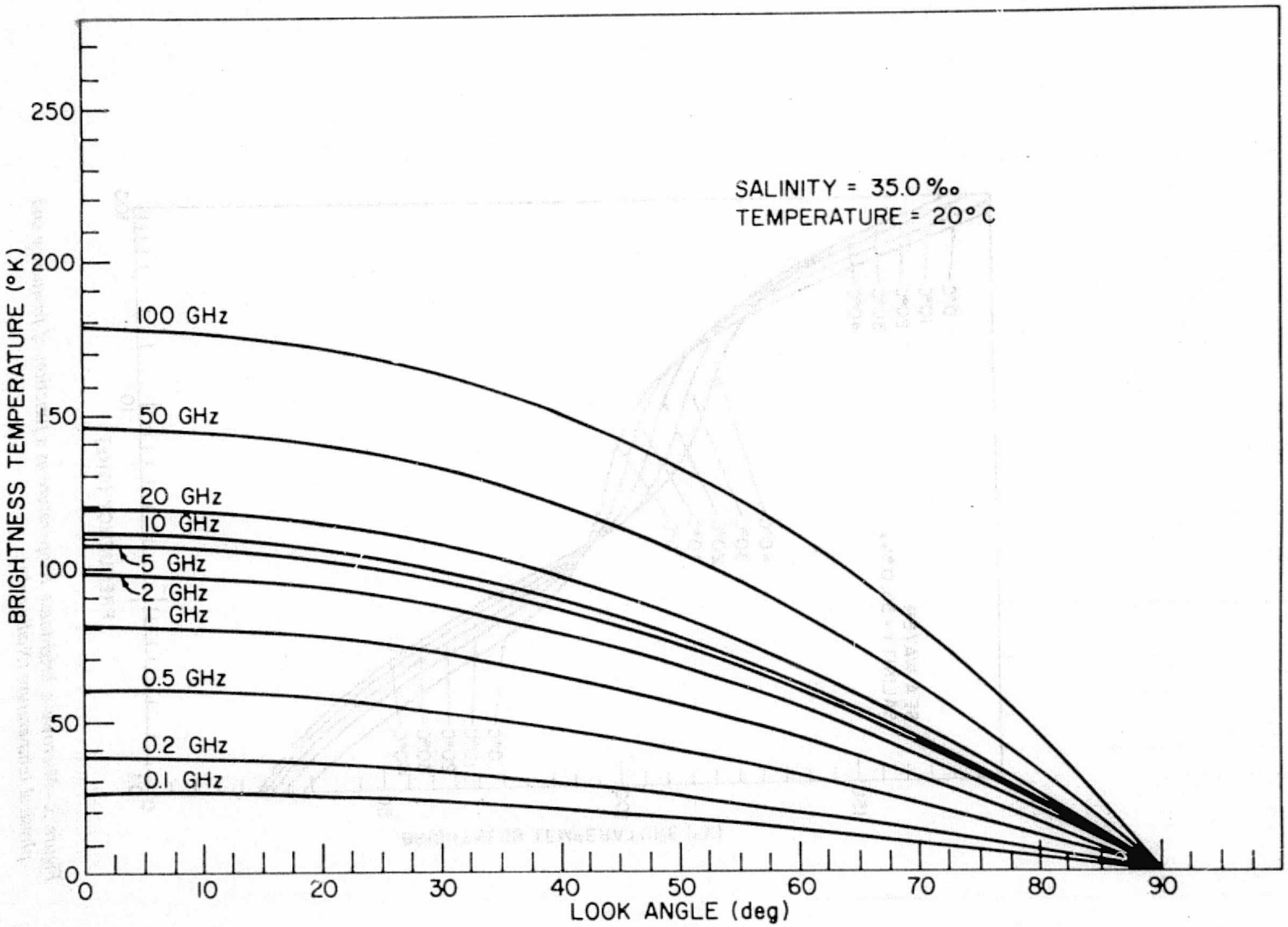


Figure 2.–Horizontally polarized microwave brightness temperature of the ocean surface.

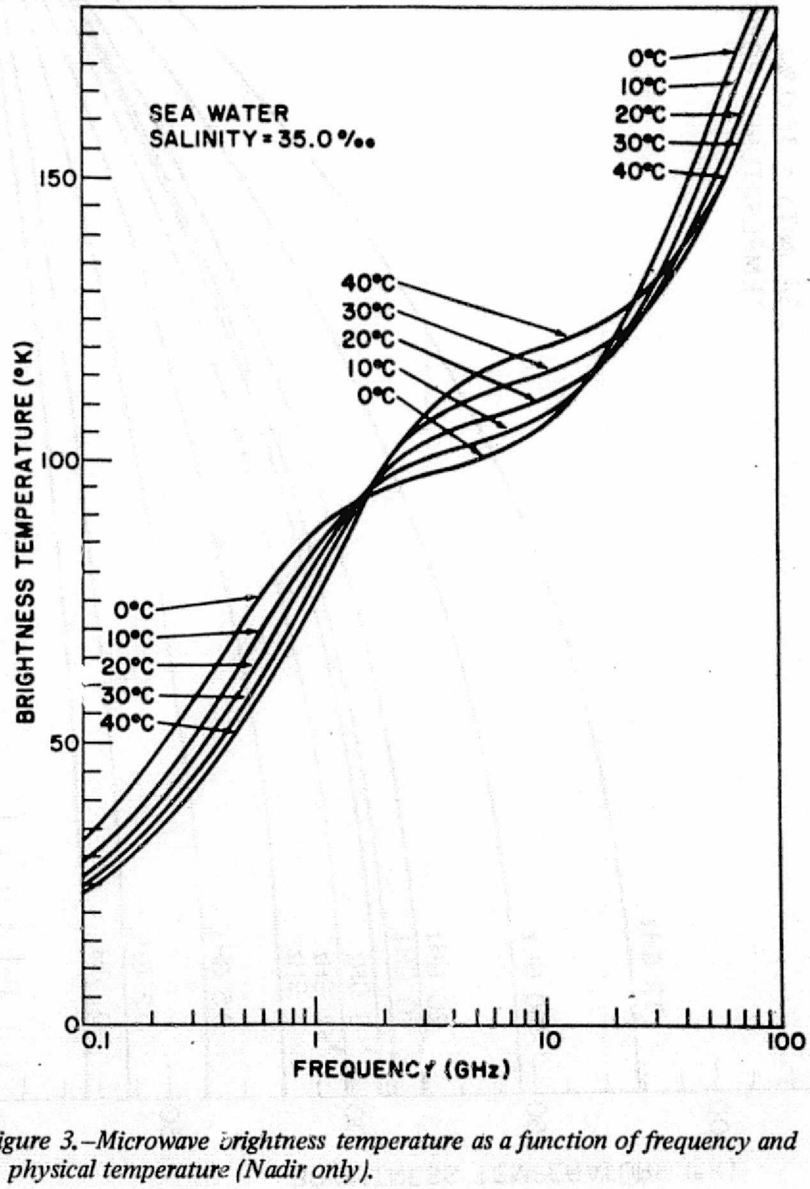


Figure 3.–Microwave brightness temperature as a function of frequency and physical temperature (Nadir only).

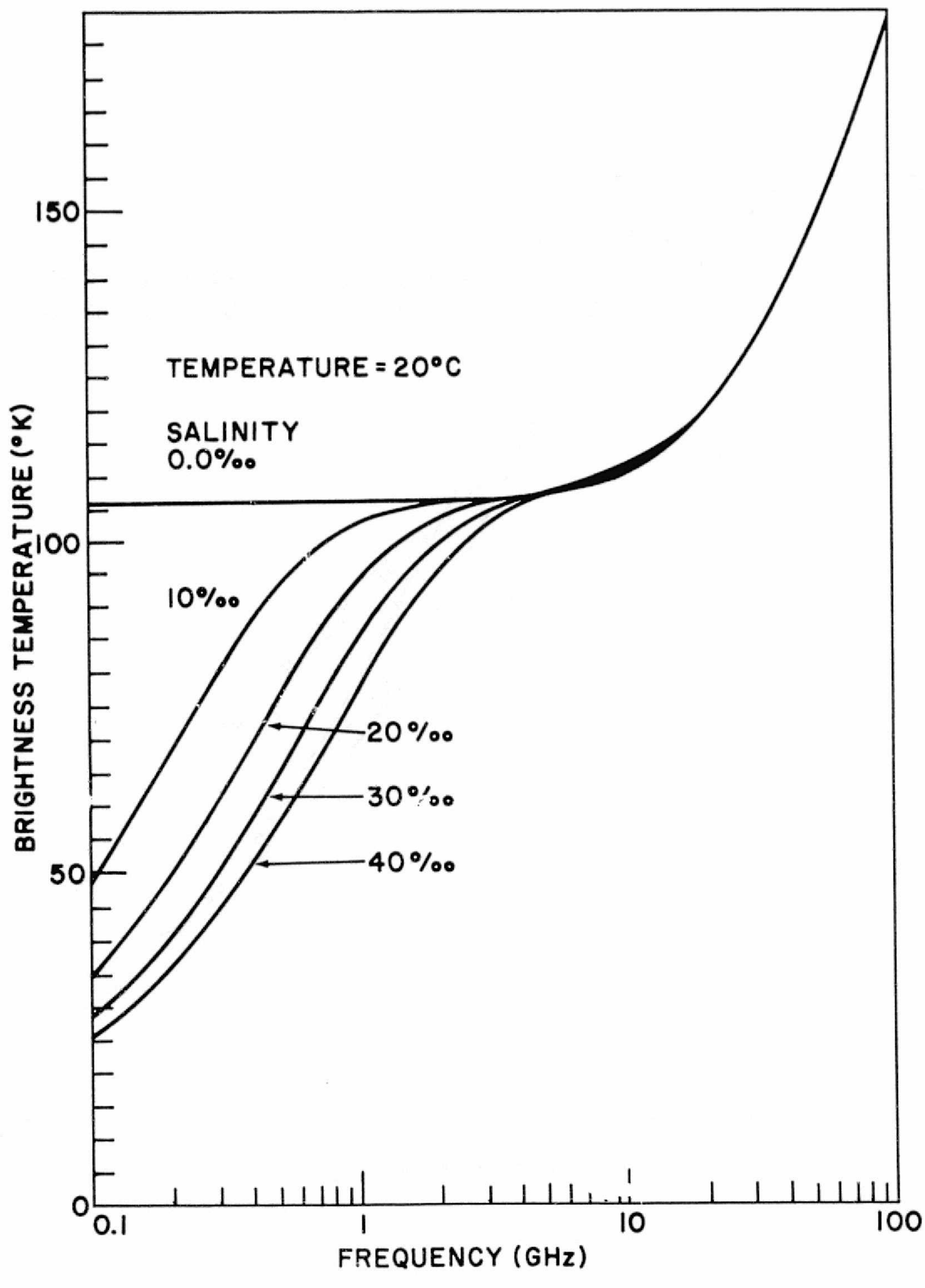


Figure 4.–Microwave brightness temperatu e as a function of frequency and salinity (Nadir only).

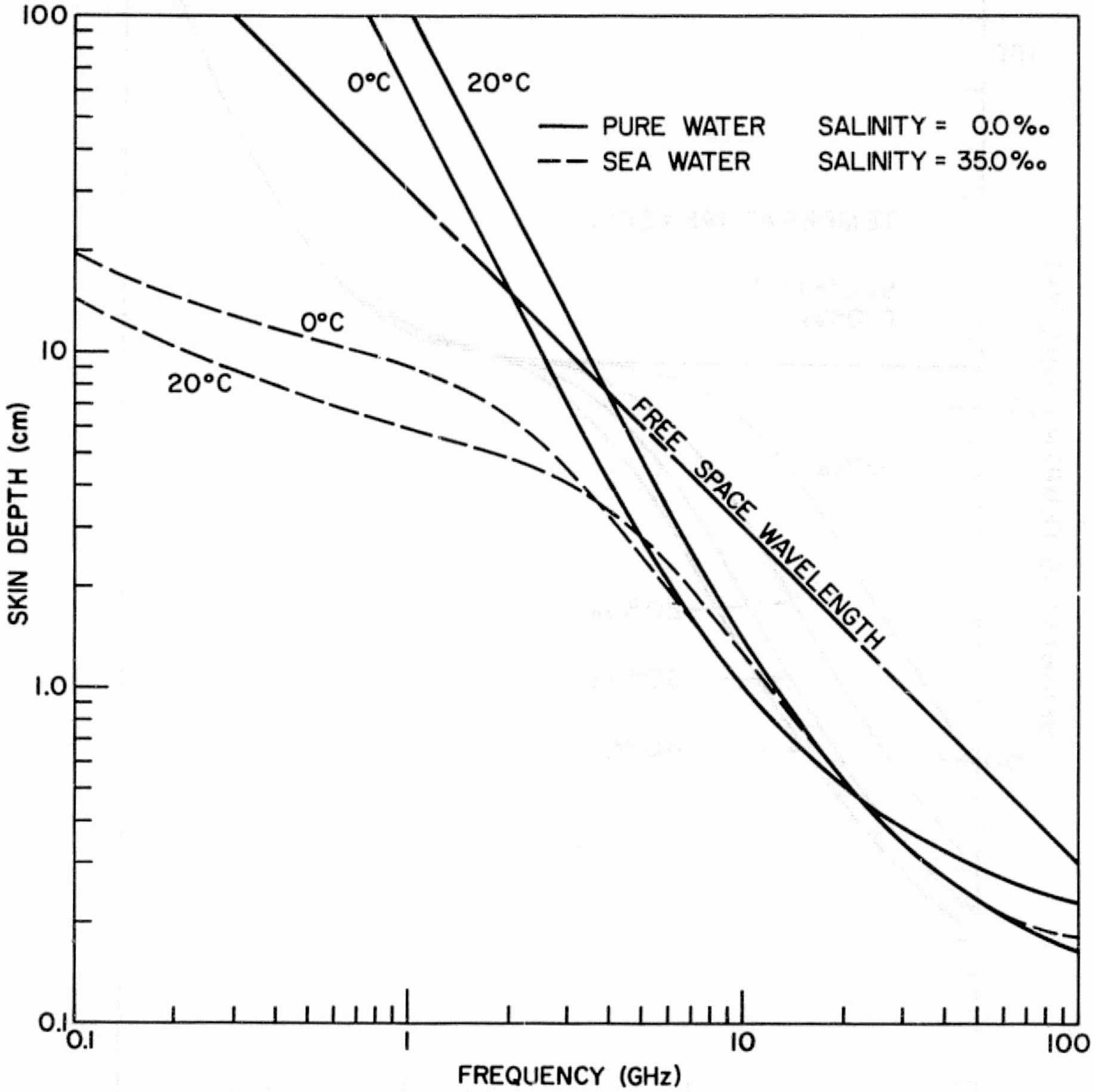


Figure 5.–Skin depth of microwave energy in the ocean surface as a function of frequency (Nadir only).

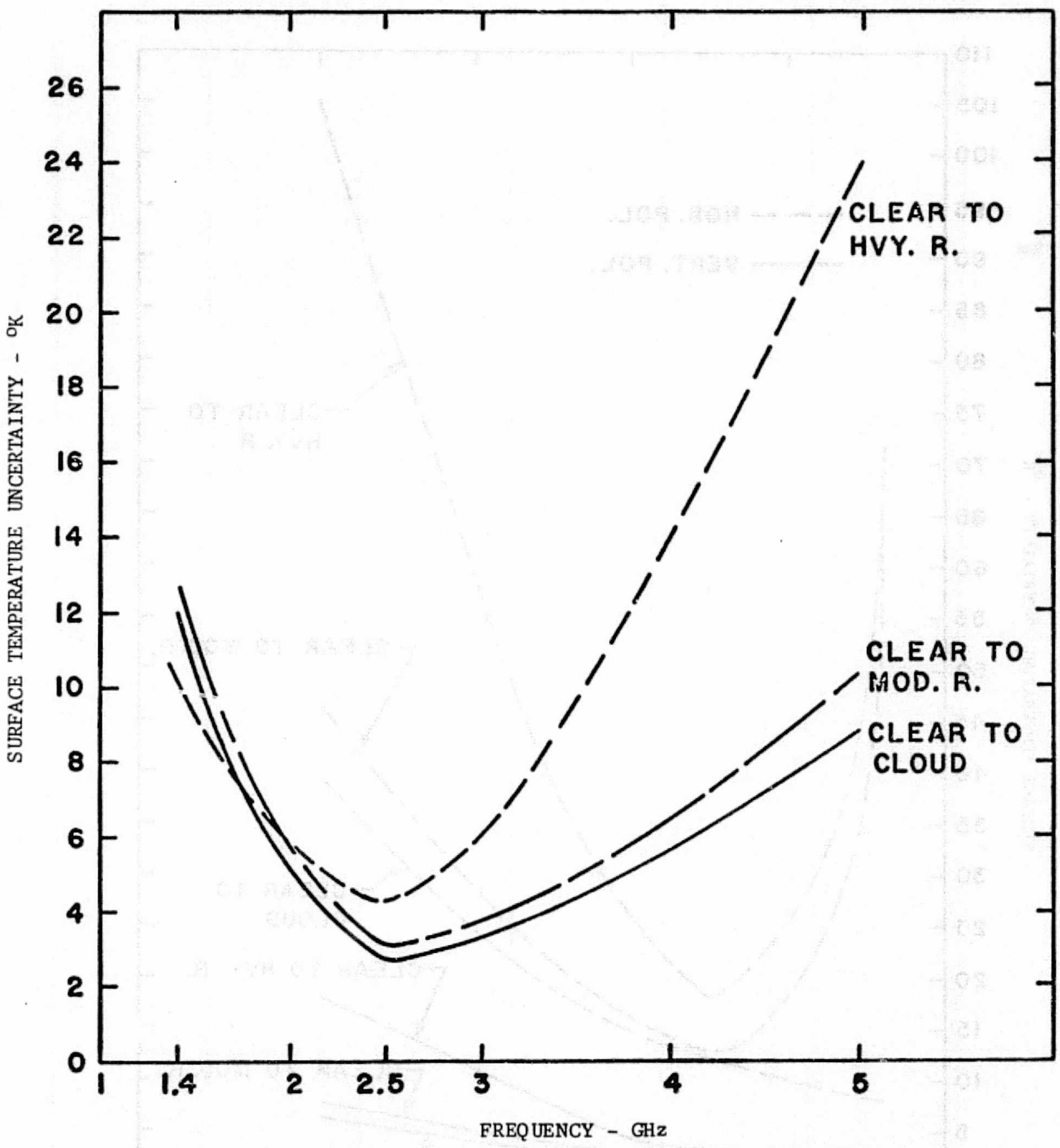


Figure 6.–Surface temperature uncertainty versus frequency for various atmospheric uncertainties (Nadir only). ($\phi_o = 0°$, both pol., $W = 4$ m/sec, $S = 33\%$, $T_{ref} = 284°K$).

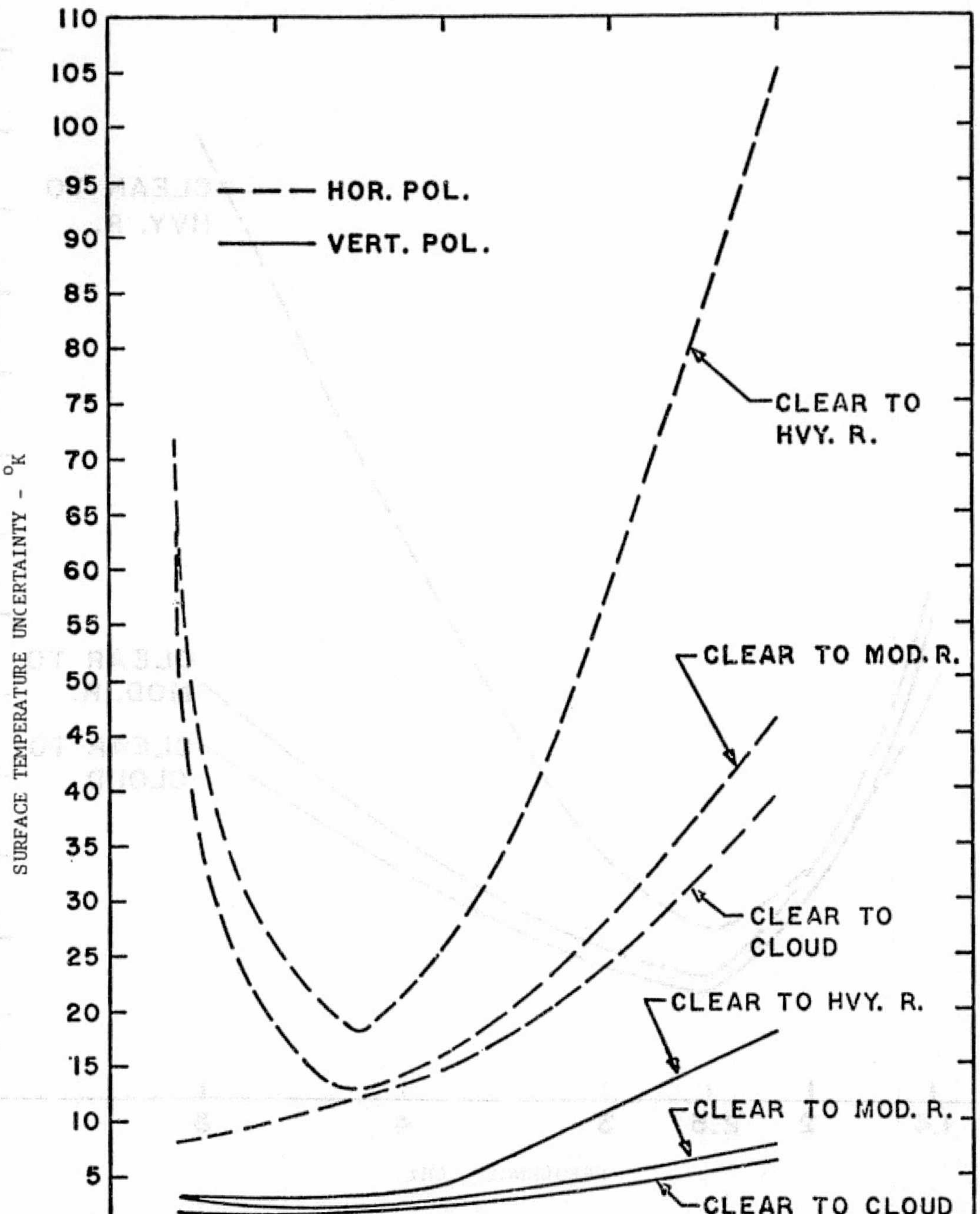


Figure 7.–Surface temperature uncertainty versus frequency for various atmospheric uncertainties. (φ_O = 60°, W = 4 m/sec, S = 33%, T_{ref} = 284°K).

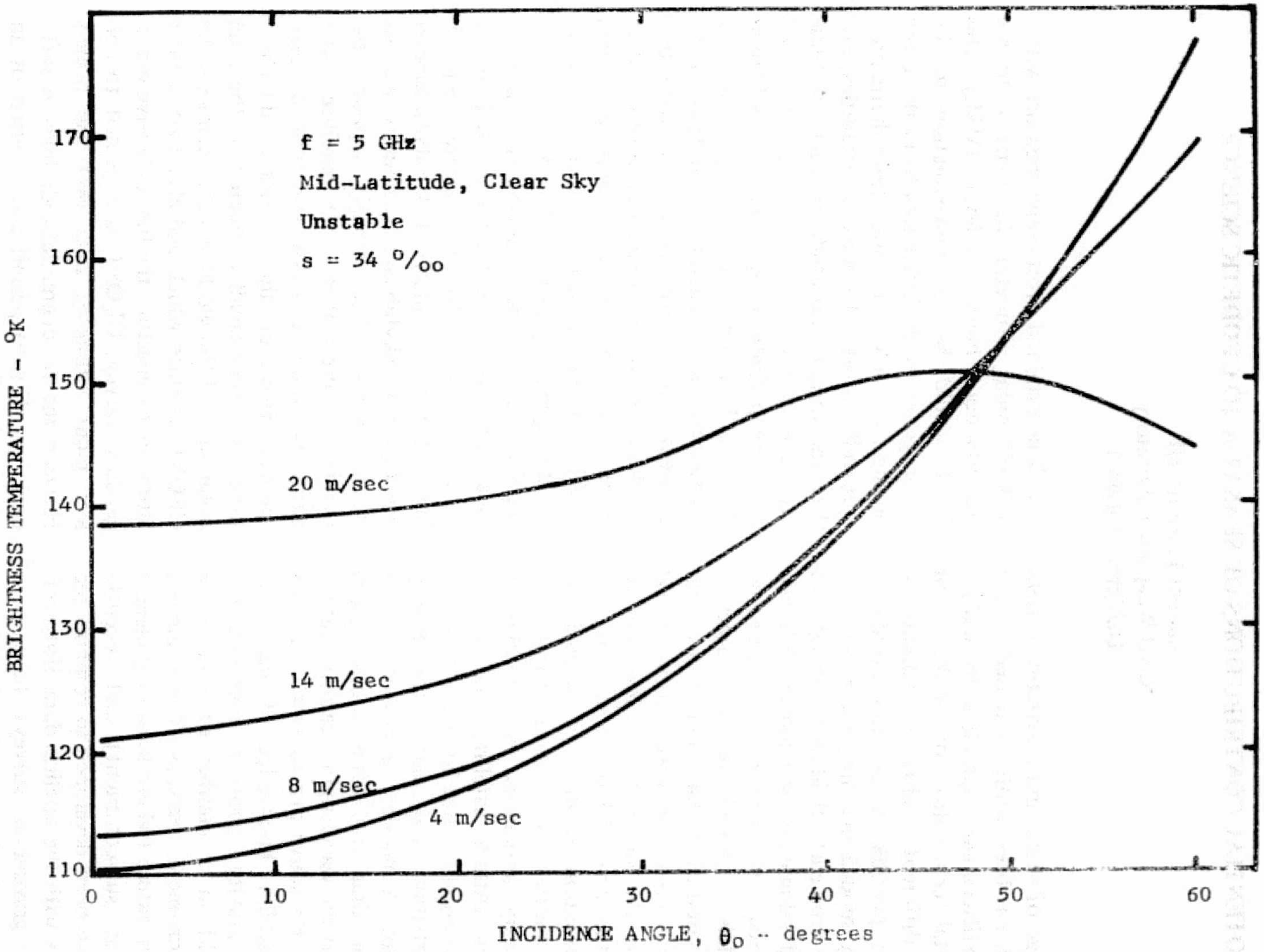


Figure 8.–Microwave brightness temperature at 5 GHz versus angle of incidence for several surface wind conditions.

POTENTIAL CONTRIBUTIONS OF SEASAT-A TO GEODETIC SCIENCE

Samuel L. Smith III
Naval Weapons Laboratory
Dahlgren, Virginia

Knowledge of shape and gravitational field of the earth has been vastly increased by the advent of artificial earth satellites. By analyzing the orbital perturbations of a multitude of satellites at different heights and inclinations, it has been possible to develop worldwide earth gravity models that are good representations of the true earth field at wavelengths of about 1500 kilometers and longer. Interestingly, a principal benefactor of the improved gravity models has been increased accuracy in computing satellite orbital ephemerides, with the ephemeris errors decreasing from several kilometers in the late 1950's to less than 10 meters in the early 1970's. Extending the orbit perturbation method of analysis to derive the shorter (than about 1500 kilometers) gravity anomalies with confidence requires low altitude satellites and at low altitudes atmospheric drag becomes the dominant perturbation and masks the gravity perturbations. A possible approach in this area are the drag free (drag compensated) satellites, but the wavelengths are still relatively long and no active program exists at this time. Classically, knowledge of the short wavelength gravity anomalies preceded the satellite field in a number of areas from extensive gravimeter surveys. These surveys were local in nature (where local may mean a continent or sub-continent) and recently methods have been developed to combine the local surveys with the satellite data. However, these local gravimeter surveys have been principally over land areas, thus leaving the oceans which make up most of the world area without data at the shorter wavelengths. As an alternative to extensive ocean gravimetric surveys by ship, which are expensive and time consuming, it was proposed that a satellite in a well determined orbit could measure with a suitable radar altimeter the distance to the instantaneous mean sea level (IMSL). This IMSL would be an approximation to the ocean geoid, with differences from the geoid arising from tides, currents, atmospheric pressure cells, orbit ephemeris uncertainties, etc. The maximum magnitude of each of these effects is of the order of 1 or 2 meters and most are periodic or quasi-periodic where as the geoid is stationary over time periods being considered here. Therefore, multiple measurements could probably provide data that would allow analysis to remove most if not all of the error sources. Also independent data could help remove such errors as due to tides or atmospheric pressure cells. Accuracies in the final ocean geoid obtainable from satellite radar altimetry have been predicted in the range of 5 meters to 10 centimeters depending on the system analyzed. A radar altimeter was flown on Skylab and preliminary analysis of the Skylab data strongly supports the theoretical predictions that satellite radar altimetry could be a powerful tool of ocean geodesy. However, the amount of data collected was very small compared to the total ocean area of the world and it remains for the GEOS-C satellite which will also carry a radar altimeter to institute the first extensive ocean geodesy survey. GEOS-C is expected to collect radar altimetry data over the oceans between the 65 degree latitude lines in sufficient quantity to permit computation of an ocean geoid with precision of 2 or 3 meters and area averages over about $5^\circ \times 5^\circ$ (about 550 kilometer squares). Naturally much more detailed geoid information will be obtained along the satellite ocean track and there is hope that GEOS-C will continue to perform

past its nominal lifetime, in which case it could collect sufficient data for a 1° x 1° (about 100 kilometers square) geoid.

SEASAT-A will provide the next significant step in ocean geodesy by having greater measurement accuracy, higher resolution and wider ocean coverage than GEOS-C. The coverage will be between the 72° latitude lines, giving data on most of the non-permanently frozen ocean areas. The orbit is designed to give at least one ocean track every 10′ (10 nautical miles) at the equator, and this density of data should allow a 0.°5 x 0.° 5 (about 50 kilometer squares) geoid to be established and along track perturbations of about 20 kilometers to be measured. The high range measurement precision (about 10 cm) of the radar altimeter will allow much greater accuracy in the derived ocean geoid, providing the oceanographic perturbations (including sea-state) can be properly corrected for. It is a potentially significant quality of SEASAT-A that it carries other instruments to measure oceanographic quantities simultaneously with the radar altimeter measurements.

The data gathered by SEASAT-A when properly combined with terrestrial gravimeter data and orbit perturbation data will allow a true worldwide geoid and gravity field with high accuracy and spatial resolution to be computed. This is a highly significant development in geodetic science which has application in numerous other fields such as navigation, orbit computation, etc. Research into methods of efficiently representing large blocks of geodetic data will be stimulated: that is, what is the best method of modeling, point masses, tesseral harmonics, sampling functions, etc.? Knowledge of the stationary geoid will aid in future oceanographic investigations of current systems and similar phenomena. Precise knowledge of the earth's gravity field might possibly be useful in the development (or checking) of dynamic earth models especially over long time periods.

Finally, it is probable that new and presently unpredicted things will be learned from the SEASAT-A data. It is the usual result in scientific research that new refined data lead to the discovery of previously unsuspected physical phenomena.

N76 11504

SATELLITE MEASUREMENTS OF OCEAN WAVES

Robert H. Stewart
Scripps Institution of Oceanography
La Jolla, California

DEFINITIONS

The surface of the sea varies randomly in time and space, and its motion is the result of many forces producing a wide range of wavelengths—from millimeters to thousands of kilometers. The undulations with wavelengths between 1000 and 0.02 meter are usually called gravity waves; they are generated by the wind, and their properties are a function only of water density and gravity. Waves shorter than 2 cm, capillary waves, are dominated by surface tension. Longer waves are produced by currents, tidal forces, earthquakes, etc.

The statistical properties of gravity waves vary slowly in time and space. As such they can be described locally by a three-dimensional Fourier transform, $X(k,\phi,\omega)$. That is, the sea surface can be considered as a superposition of waves of all wavelengths, $L = 2\pi/k$, and periods, $T = 2\pi/\omega$, traveling in all possible directions ϕ. Usually it is assumed that the larger waves ($L > 1$m) obey the dispersion relation applicable to infinitesimal amplitude gravity waves, $\omega^2 = gk$. This reduces the dimension of the spectrum by one and the resulting function is the directional spectrum ψ (k, Φ) = ψ_1 (ω,Φ). The sea surface is now described as a superposition of plane waves having various wavelenths and directions. Integration of ψ over all angles yields the one-dimensional spectrum Φ (ω). This is the same as the sea surface elevation measured at a point. Integration of Φ over ω gives the variance of wave height at this point, $<\zeta^2>^{1/2}$. This statistic is frequently reported in terms of the significant wave height, $H_{1/3}$, which previously was not well defined but is now generally taken to be $H_{1/3} = 4 <\zeta^2>^{1/2}$. This is a correctly defined function, but it is not quite the same thing as the original meaning of the term.

MEASUREMENTS

The statistics of the ocean surface, especially the statistics of wave number distribution, are poorly known. In fact, $X(k,\phi,\omega)$ has never been measured. In discussing what is known about the various spectra, it is convenient to consider the simplest first.

The wave-height variance, or root-mean-square wave height $<\zeta^2>^{1/2}$, is easily estimated, and is the most commonly reported statistic. Most data comes from "eyeball" estimates of wave height reported by passing ships, less commonly from accelerometers on weather ships and buoys. Large amounts of data are available: Atlases give wave climate over the world's oceans; wave height is routinely included in ship's weather reports; and wave height is routinely predicted by such groups as the Fleet Numerical Weather Central. This latter group claims, with some justification, that their wave prediction models are good enough for present applications such as optimum ship routing, and that $H_{1/3}$ need not be measured in the future.

The one-dimensional spectrum is commonly measured with wave staffs or accelerometers mounted on buoys and ships. The general shape of the function and its relation to wind speed, duration, and fetch are reasonably well known for wavelengths greater than one meter. Little is known of ϕ (ω) in the region between one meter and one centimeter because few measurements have been made. The equivalent function ϕ (k) is almost unknown for these wavelengths because the dispersion relation $\omega^2 = gk$ cannot be applied

accurately to short waves. This has important consequences. Microwaves are Bragg scattered by ocean wavelengths in this band, and lack of knowledge of these waves hinders to some extent the usefulness of active microwave systems that use sea scatter for measuring such things as oceanic winds. Conversely, the Bragg scatter can be used to investigate this wavelength region of ϕ.

The directional spectrum ψ (k, ϕ) is not well known. It has been measured a few times in a few selected places, but its dependence on wind speed, duration, and fetch are yet to be adequately described.

The general spectrum of the sea surface, $X(k,\omega,\phi)$ has never been measured.

SATELLITE MEASUREMENTS

Satellite measurements of the directional spectrum of ocean waves are expected to have a number of important benefits to pure research, ocean engineering, and marine activities. Measurements of $H_{1/3}$ are of less importance because it is already well known and predictable for usual oceanic conditions. But this may not be true for extreme wind speeds, particularly over long fetches (such as in the Antarctic circumpolar region), so additional measurements during these relatively rare conditions may be useful.

Measurements of the directional spectrum are particularly important. First of all, and this hardly needs saying, development of the satellite instruments will lead to simple, reliable techniques for measurement of the spectrum. This in itself is important even if it is never used from a satellite. But suppose a technique is developed, what are the benefits of knowing more about ocean waves?

For pure research, measurements of the spectrum as a function of wind speed and fetch can be used to test theories of wave generation; to date, only a few measurements of wave growth have been published. Measurements near the edge of strong currents can test theories of wave trapping and refraction by current shears; the effect can be strong but has never been measured. And measurements made in conjunction with simultaneous oceanic internal wave fields can test theories for the generation of internal waves by surface waves: these waves have often been measured, they effect the propagation of sound in the sea, but there exists no generally accepted theory for their generation.

Routine measurements of wave size and direction will lead to reliable catalogs of wave climate of benefit to marine engineering and activities. A few examples can be listed. Offshore structures are designed to withstand the largest expected waves from a particular direction; improved catalogs will lead to more reliable and safer designs. The siting and design of breakwaters and harbors depends on the expected direction of arrival of large waves; again, this data can be supplied by satellite. Ships are slowed and their cargo damaged by large waves. If the oceanic wave field were known and predictable ship routes could be optimised for most economic operation, the wave field will be measured by satellite, and its future development will be predicted from the improved models of wave generation that are themselves produced from satellite data.

Wave measurements from satellites may have an unexpected side benefit. The measurements will almost certainly use active microwave systems which observe the scatter from short (cm) ocean waves. Development of these techniques will contribute toward an understanding of these short waves or microstructure of the sea surface. And this, in turn, will help illuminate those processes that govern the transfer of heat, water vapor, and momentum across the air-sea interface. Thus satellite measurements will make an indirect contribution to a long standing and difficult problem.

REFERENCE

Kinsman, B., 1965. *Wind Waves*. Prentice. Hall.

N76 11505

PHYSICAL OCEANOGRAPHY FROM SATELLITES: CURRENTS AND THE SLOPE OF THE SEA SURFACE

W. Sturges
Florida State University
Tallahassee, Florida

The study of transient processes can be enormously aided by a global observation network. *Bryan* (this report, 1974) described this work. It may not be so obvious, however, that merely *finding* the path of a major current—Gulf Stream, Kuroshio, Somali Current, Brazil Current, etc.—is not a trivial task. To infer sea surface height for this purpose, a single-pass precision of ∿ 10 cm and an orbit-to-orbit stability of ∿ 5 cm would be adequate. It is well known that a great deal of effort is required, for example, to map the Gulf Stream position by infrared scanners from airplanes. The work in the Gulf of Mexico to trace out the path of the loop current (by George Maul and others) is another well-known example. The resolution required increases as the strength of the current decreases. A global scheme using altimetry in conjunction with thermometry techniques offers many advantages. The meanders of the boundary currents are well documented, and it is a straightforward problem, oceanographically, to find them, for a variety of beneficial purposes. As an operational measure, however, satellite coverage seems the only feasible method.

The discrepancy between oceanic leveling and land leveling has been discussed (*Chovitz,* this report, 1974; *Sturges,* 1974). This problem arises in most countries that have first-order leveling networks, so its solution would be of importance to other than just the U.S. (e.g., *Hamon and Greig*, 1972). In the U.S. it should be noted that there are two features to be investigated. The first is the discrepancy in the slope of mean sea level from north to south along both the Atlantic and the Pacific coasts.

The second feature is the change of 70 cm in mean sea level between the Atlantic and Pacific coasts of the U.S. On this point the oceanic and land leveling agree, but it is my impression that many geodesists do not believe that the leveling results are sufficiently accurate for this comparison.

Two serious problems remain to be overcome in these applications. The first is that there appears to be a high "noise" content in the altimetry signal (depending on one's point of view). The removal of tides, atmospheric pressure fluctuations, wave noise, and geoidal undulations raises substantial barriers. The second difficulty is one of sampling technique. The dominant ocean "noise" caused by low frequency variability (e.g., *Bryan*, this report, 1974) has space scales of ∿ 100 km and time scales of a month or so. The signals can be filtered or corrected for tides, etc., but the sampling schemes must be carefully planned, both in space and time, to prevent serious aliasing of the ocean-current information by the low frequency variability in the ocean.

REFERENCES

Hamon, B. U., and M. A. Greig, 1972, Mean sea level in relation to geodetic land leveling around Australia. Jour. Geophys. Res. *77,* 7157-7162.

Sturges, Wilton, 1974, Slope of sea level along continental boundaries. Jour. Geophys. Res. *79*(6) 825-830.

N76 11506

EXPECTED SCIENTIFIC YIELD OF SEASAT-A AND ITS APPLICATION TO CORPS OF ENGINEERS PROGRAMS

P. G. Teleki
Coastal Engineering Research Center
Corps of Engineers
Fort Belvoir, Virginia

The following statement describes projected scientific-engineering yield of the ocean dynamics satellite, SEASAT-A. It is based on information available as of 6 May 1974.

BACKGROUND INFORMATION

The River and Harbor Act of 1968 (Public Law 90-483) assigned the special responsibilities for studying, investigating, and appraising the condition of the Nation's shorelines and for their protection, restoration, and management to the U.S. Army Corps of Engineers. The National Shoreline Study found 20,500 miles of ocean and Great Lakes shorelines in severe erosion. Priority was assigned to 190 miles of these shores at an estimated cost of $240 million (Report on the National Shoreline Study, 1971).

It is also common knowledge that shores and beaches have experienced a tremendous surge of activity in the last 15 years. The categories of these activities are recreation, natural resources, seaports and commerce, residential and commercial construction all of which are underlined by an ever increasing migration of population to the coastal zone. It is not the beaches only which have become the focus of interest but the estuarine areas and continental shelves as well.

These facts illustrate the need for scientific-engineering information for the coastal zone to their management, to the practice of preventive engineering, and to the operation and maintenance of existing natural and man-made features. The needed information can be classed as synoptic for the recognition of megascale phenomena and for climatological assessments and basic science necessary for the solution of outstanding problems in the disciplines of physics, chemistry, and biology applied to coastal phenomena.

The Corps of Engineers interest in SEASAT-A is a natural outgrowth of its mission to protect and manage the Nation's shorelines and it is documented by its participation in the planning phase of this ocean dynamics satellite. This is not to say that only coastal zone data, produced by the SEASAT program, will be useful to the Corps' Districts and Laboratories. In the research phases of coastal oceanography and coastal engineering, some deep-ocean data will also be necessary as input to nearshore research. These requirements are described below.

SCIENTIFIC EXPECTATIONS AND PROBABLE GOALS

In regard to the expected payload on SEASAT-A the following general study areas can be identified: gravity waves, wind waves, wind-wave interaction, storms and hurricanes, ice, coastal currents, tsunamis, and to a very small extent geoid modelling as it applies to determination of sea level and tides. All but waves can be considered to have secondary importance. It is realized, however, that sufficient interdependency of measurements and instrumentation exists to elevate secondary interests to primary status at certain sites and under certain environmental conditions.

WAVES

In the coastal zone accurate measurements of waves are of the utmost importance to practically all phases of coastal engineering

research. Although the wave gauging program of the Coastal Engineering Research Center has been providing significant information on wave height and wave frequency distributions for several locations along the Atlantic, Gulf, and Pacific coasts, determining wave direction has not met with unified success. Thus, information on the directional spectra of waves, to be provided by the imaging radar, to fill in this gap is most welcome. Besides the scientific value of a directional spectrum in itself, other uses are also envisioned, namely for studies on refraction and diffraction of water waves which in turn can serve as input to shoaling and navigation problems and selection of sites for engineering works.

Waves in the coastal zone produce the primary forces to which coastal structures are subjected, consequently knowledge of the potential wave heights of a coastal area, statistically averaged, is important in the adequate design of such structures. Generally, design criteria are based on expected worst conditions, derived from climatological data and wave hindcasting. In many instances, however, storm- (e.g., hurricane-) generated combined wave and wind conditions can be of such magnitude and duration to exceed all past records of experience, thus exceeding set design criteria. It naturally follows that if it were possible to gauge the winds and waves in or near the eye of storms, valuable information to the prevention of loss of lives and reduction of property damage could be had through forecasting or modeling. The SEASAT imaging radar holds promise, in the L-band mode, to attain this objective.

In regard to an "average sea," the required accuracy of wave measurements are estimated to be (a) significant wave height, $H_{1/3}$ ± 1 foot for $H_{1/3} < 10$ feet, $H_{1/3}$ ± 10% for $H_{1/3} > 10$ feet; (b) wave period, $T \pm 1$ sec for $6 < T < 20$ sec; (c) direction $\theta \pm 10°$ for deep water and $\theta \pm 3°$ for water depth < 200 feet. Data of lesser accuracy would probably change their value from the quantitative to the qualitative.

It appears then that imaging radar data could be usefully supplemented with wave height information (means and variances) obtained from the altimeter. This can make the altimeter important to areas where direct measurements by sensors are not available or in the pre- and post-launch phase of the satellite for correlation of its data to "ground truth" provided by wave gauges deployed in coastal areas. It must be noted, however, that if the water spectrum is obtained from the SAR (as opposed to the slope spectrum) or if an adequate transfer function from the slope to the surface spectrum is available, it may be redundant to consider wave height data from the altimeter.

WIND WAVE INTERACTION

Recognizing the need to separate the gravity wave spectra from wind wave spectra, certain useful information is expected from the scatterometer. The Corps views this instrument in the low priority category, because its ultimate function is to provide wind velocities and directions which are not of research or operational interests to this office, and because the data are predicated upon choosing a model for the water-to-air transfer mechanism. The scatterometer records only the statistics of the returned signal. Interpretation of these statistics must, at this point in time, be based on conceptual models, not fully verified, as the structure of radar return signals relevance to wind speed can only be corroborated from laboratory results where wind wave generation is quite different from nature. The relation between radar return and the observed capillary state may be correct but the identification with natural wind velocities is not yet on firm ground. Since steep, large amplitude waves typical of the coastal shoaling zone will shield wave troughs from the free wind, the statistics of ripples may produce wind speed estimates too low for high winds. It appears, therefore, that if sea state is to be depicted correctly, one must

view scatterometer data side-by-side with imaging radar return. This is especially true for overcast conditions.

In summary of wave data requirements the single most relevant instrument is the imaging radar whose return can be supplemented with scatterometer and altimeter data for their mutual enhancement.

ICE

Several aspects of research on sea ice are expected to benefit from the SEASAT program and in particular from the SAR. The physical information of primary interest lies in sea ice topography (roughness characteristics) in ice lead mapping, and in effective thickness measurements. An imaging mode, as represented by SAR, is crucial for these studies and results from it are viewed economically beneficial in regard to both navigation and prevention of damage to structures in the Great Lakes and Alaska. This statement does not exclude relevance of the altimeter, scatterometer, or IR scanner from applicability to ice research; although it does assign secondary importance to them. It has been noted that the Northern Slope of Alaska may only receive partial SEASAT coverage. A change of the orbit to 80° could alleviate this problem.

The remaining categories, such as currents, sea level determination from geodesy, and tsunamis, are of passing interest at this time. Since temperature variations are minimal in the coastal zone and have little influence on wave forces and propagation, the temperature measuring capability of SEASAT is not expected to provide significant information to programs of the Corps of Engineers. There is basic scientific interest in and expectation from efforts to produce an ocean geoid model to be related to its equivalent over land masses. As for tsunamis, forecasting this phenomenon would best serve coastal areas.

The preceding dealt primarily with basic research interests and their expected application to solving coastal oceanographic problems. Another aspect must still be touched upon, namely operation and maintenance of existing structures and facilities and the forecasting potential inherent in the synopticity and temporality of SEASAT-A. Both of these could well benefit from the development of climatological models for waves and winds designed to serve not only as early warning systems but to schedule offshore operations by, be these exploration, operation of offshore ports, or dredging and mining.

COVERAGE AND DATA REQUIREMENTS

Requirements for real-time data have not been identified to date. Although most of coastal and polar U.S. waters are of significance to Corps research projects, only selected samples from the imaging radar are expected to be used during SEASAT-A operations. There is concern for all facets of on-board data integration, the manner and effects of transmission, the nature and effectiveness of receiving stations in handling the data streams, and in reconstruction of valid records in image and digital forms as well as analog traces where applicable. There are elements of expectation and capability which are superimposed, best determined from pre- and post-launch calibration of all sensors.

It is expected, therefore, that for the duration of the first satellite, small amounts of data from selected sites will be requested for analysis and that these will have to be coordinated with existing research programs.

SUMMARY

The total SEASAT system is viewed as a prototype multispectral-multimission experiment. The imaging radar is considered essential to this system and in trade-off with other sensors outweighs them individually. Its applicability to various phases of coastal oceanographic research has been demonstrated, and if this sensors data are regularly correlated to real-time information of other instruments and precise orbital position the results are

expected to be of significant benefit to programs of the Corps of Engineers. This point cannot be overemphasized. Despite weight and power requirements, the SAR can provide better resolution than all other sensors.

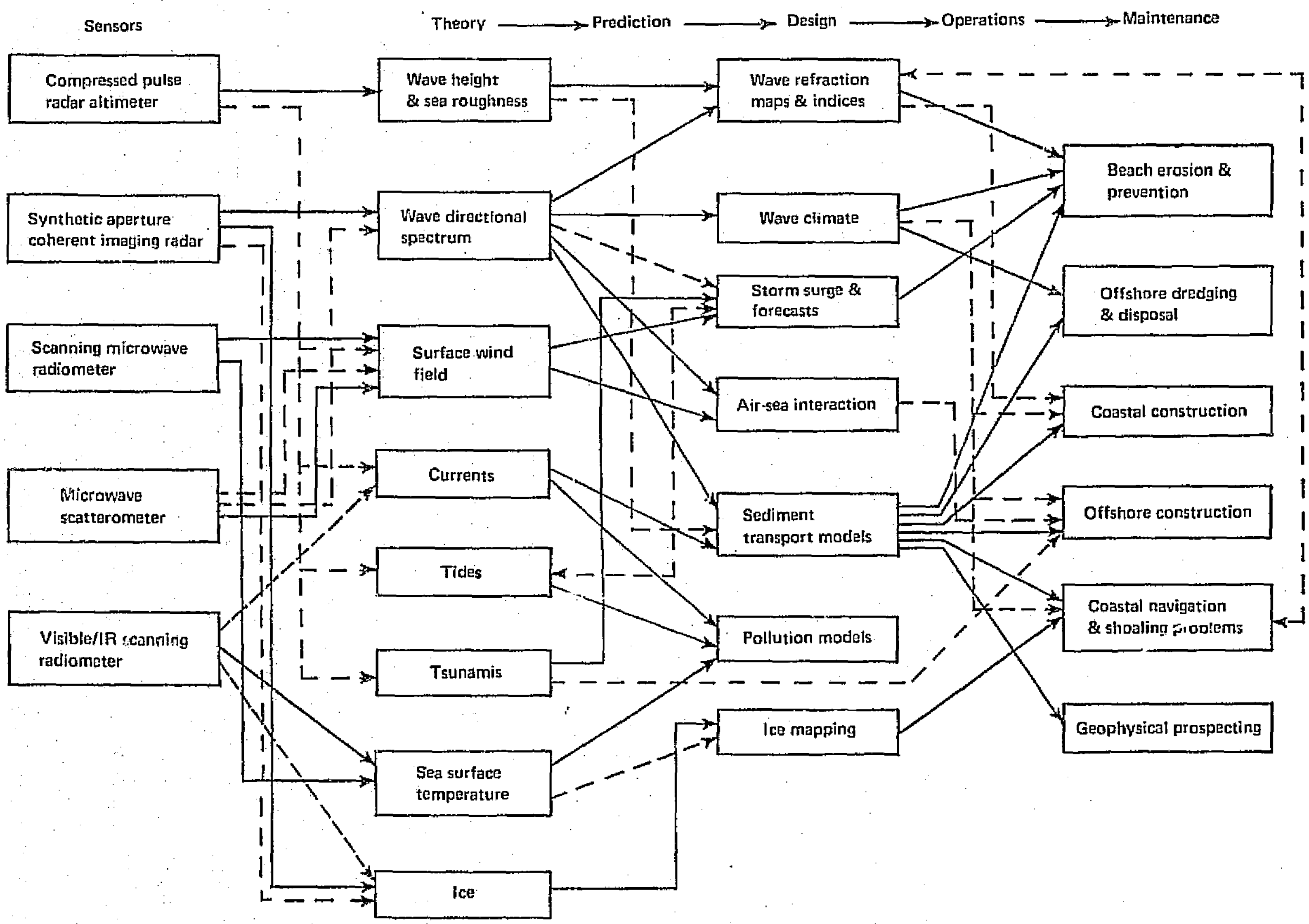


Figure 1.–SEASAT scientific uses in coastal engineering.

N76 11507

SEASAT AND FLOATING ICE

W. F. Weeks
Army Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire

Even though the planned orbit of SEASAT-A is hardly an optimum one for studying sea ice in that the main Arctic Ocean will not be covered, data will still be obtained from very large and important areas of sea ice located at latitudes below 72°. In the southern hemisphere this includes essentially the complete pack ice area of the Southern Ocean. In the northern hemisphere, coverage will be obtained of most of the coastal ice zones of the Beaufort, Chukchi, Siberian, Laptev, Kara and Barents Seas, as well as the southern portions of the Baffin Bay – Labrador Pack and the East Greenland Drift Stream. In addition complete coverage will be available of the ice in the Bering Sea, the Sea of Okhotsk, Hudson's Bay, and the Gulf of St. Lawrence. Useful imagery should also be obtained of the fresh-water ice in the Great Lakes – St. Lawrence Seaway system.

These areas encompass essentially all the regions where floating ice has a major impact on the activities of man: the resource rich continental shelf areas of the Arctic (in particular those off Alaska and Siberia), the entrances to the Northwest Passage through the Bering Strait and Baffin Bay, the North Sea Route along the Siberian coast, the complete Great Lakes–St. Lawrence Seaway–Gulf of St. Lawrence transportation system and the iceberg drift routes in the North Atlantic.

The data collected by SEASAT would be useful in developing predictive physical models for the drift and deformation of sea ice, for estimating the heat budget of the polar seas, for the optimum routing of shipping through pack ice areas, for the design of both offshore structures and shipping capable of surviving in heavy pack ice, and for the tracking of large icebergs and ice islands. A SEASAT ice program would therefore make major contributions to the Arctic Offshore Program that is currently being developed by NSF to provide the environmental and engineering data needed for the safe development of the resources of the Alaskan continental shelf. It would also contribute to the POLEX program which will explore atmosphere/ice/ocean interactions in the Polar Regions and their effect on world climate.

The instrument package for SEASAT-A is particularly useful for studying sea ice in that the Coherent Imaging Radar (CIR), the Scanning Multifrequency Microwave Radiometer (SMMR) and the Compressed Pulse Radar Altimeter (CPRA) are not limited by the presence of clouds. The CIR will undoubtedly be the most useful system in that it will provide information on the edge of the pack and the fast ice, on the presence and geometry of leads within the pack, and on the distribution of belts of highly deformed ice. The SMMR system will supplement this in that it will also locate the edge of the pack as well as providing information on the amount of different ice types that are present as well as their areal extent. The CPRA system should provide running estimates of the mean free-board of the ice under the satellite as well as the mean roughness of the sea ice surface. It should be most interesting to compare the CPRA results with the CIR data and with independent laser estimates of the roughness of the sea ice surface. It is quite possible that this calibration will allow one to make quantitative estimates of sea ice surface roughness. This is quite important in that the force that

the wind applies to the upper ice surface is a function of surface roughness. We know that the surface roughness of sea ice undergoes major changes throughout the year but the magnitude and pattern of this change is not understood. It is also possible that the Infrared Radiometer (IRR) will be useful in estimating the overall heat flux from the ocean, through the ice and leads, to the atmosphere. This system is, however, not useful during periods of heavy cloud cover.

III. THE EARTH AND OCEAN PHYSICS APPLICATIONS PROGRAM (EOPAP)

OCEAN DYNAMICS PROGRAM

THE EARTH AND OCEAN PHYSICS APPLICATIONS PROGRAM (EOPAP)

OCEAN DYNAMICS PROGRAM

John R. Apel
National Oceanic and Atmospheric Administration
and
Joseph W. Siry
National Aeronautics and Space Administration

INTRODUCTION

During the past decade, the large strides made in space science and technology have provided us with new tools with which to undertake spaceborne observations and investigations of the dynamics of the solid earth and the oceans. First, an improved understanding of earth dynamics and earthquake mechanisms may eventually lead to the ability to predict earthquakes. Second, a better understanding of ocean dynamics, that is, waves, currents, and circulation patterns could lead to more efficient ocean use through improved forecasts of the marine environment. NASA's Earth and Ocean Physics Applications Program (EOPAP) aims at solving both solid earth and ocean problems, these two seemingly disparate subjects being cemented together by certain common elements of precise satellite orbit determination and accurate distance-measuring instrumentation. Briefly, the solid earth objectives are (1) to develop and validate methods which may eventually lead to earthquake hazard assessment and alleviation models, and (2) to refine the global geoid, or shape of the earth, to a high degree of precision. The ocean physics objectives (which must draw on certain of the results from the solid earth portions) are (1) to develop and validate means for predicting the general ocean circulation, surface currents, and their transports of mass, heat, and nutrients, and (2) to develop and validate means for synoptic monitoring and prediction of transient phenomena on the ocean surface such as wave heights and directions, surface winds, temperature, and storm surges, with an emphasis on identifying marine hazards.

The origins of the effort are to be found in the National Geodetic Satellite Program, now nearing completion after a decade of fruitful activity. A catalyst for EOPAP as such was a study on solid earth and ocean physics (*NASA*, 1969), sponsored by NASA and the Massachusetts Institute of Technology at Williamstown, Mass., in 1969. An enlargement of the concepts laid out in the founding works to include the dynamics of wind and waves was made by members of NOAA and NASA during the drafting of the EOPAP program plan (*NASA*, 1972).

NASA is working with user agencies, such as the Departments of Commerce, Defense, and Interior, in developing instrumentation and techniques, as well as longer range plans to insure that these areas receive the best technological capabilities of the combined agencies. From these mutually supportive contributions will emerge a better understanding of the phenomena involved, with the expectation that practical benefits will result. For example, meteorological satellites and the instruments they carry, coupled with analytical modelling and computerized data management, are past examples of how NASA, working in this case in support of NOAA, has assisted in making significant improvements in weather forecasting. Similarly, other technologies have been or are being developed

which will permit (a) a much better understanding of the motions of the earth's crust which produce earthquakes, and (b) major advances in monitoring and forecasting ocean-surface conditions on a near-real-time global basis.

The ocean plays as fundamental a role in the natural scheme of things as does the atmosphere, although its functions, being considerably more varied and diffuse, are probably neither as well appreciated nor as well understood. The sea profoundly affects the weather and in turn is affected by the atmosphere, acting as both a heat reservoir for storing, distributing, and releasing solar energy, and as the dominant source for atmospheric moisture. Photosynthesis by oceanic phytoplankton is one major process for maintenance of atmospheric oxygen. Geological activity on all time and space scales takes place in the seas and its beds, which serve as the repository for the detritus of man and nature and as an important, practicable source of petroleum and a few useful minerals. Its currents and dilutant powers are called upon to disperse sewage, poisonous and nonpoisonous wastes, solid trash, and excess heat, all the while maintaining a role as the *aqua viva* for an extremely complicated and commercially important food chain, and as a means of recreation and refreshment for people. In the estuaries and the coastal zones, these conflicting demands are especially severe.

However, because of the great length and breadth of the sea, and the harsh environment it presents, the difficulties in obtaining detailed, timely information of sufficient observational density across most of its expanse have prevented an effective monitoring and forecasting system for the oceans. Thus, the prediction of wave heights depends on forecasts of the time and space histories of surface winds—the latter forecasts themselves being fraught with considerable uncertainty, as the loss of ships and oil drilling rigs at sea attests. Similarly, the locations of major ocean currents are known only approximately and the data required for shipping and fishing interests to efficiently exploit currents are lacking. The lack of sufficient wind and pressure data over the oceans has precluded an improved, longer-range weather forecast for continental areas. In order to achieve an effective one-to two-week forecast, observational data are needed over the oceans with about the same frequency and density as now exist in the continental United States.

One finds a diverse list of parameters entering into oceanic processes; furthermore, many cannot be discerned from spacecraft. By and large, satellite oceanography is confined to surface and near-surface phenomena. This constraint is not as severe as it appears at first glance, because surface data taken from spacecraft can be appended with other, conventionally derived subsurface measurements of certain parameters (e.g., vertical current or temperature profiles) in order to construct a more nearly three-dimensional view of the ocean. In addition, near-surface data are useful in their own right, since the interaction between ocean and atmosphere largely takes place in the few tens of meters above and below the sea-air interface. Man's marine activities are mostly limited to that surface as well, so that the kind of two-dimensional oceanography that one can pursue from spacecraft is highly relevant.

SKYLAB EXPERIMENTS

The EOPAP Ocean Dynamics Program moved from the preparatory and flight test stage to an orbital phase with launching of the Skylab Workshop and Command Modules. This orbiting facility was outfitted with an Earth Resources Experiment Package (EREP) which included a radar altimeter, a radiometer, and a scatterometer, three instruments which are basic tools of the EOPAP Ocean Dynamics Program. The concepts on which these three new equipments were based were

actually proved in orbit during the Skylab Mission. The pulse altimeter, for example, verified for the first time by means of direct orbital measurements that the sea surface does indeed dip by some fifteen meters in the neighborbood of the Puerto Rican trench which lies to the north of this island. The depression in the ocean surface is a manifestation of an anomaly in the earth's gravitational field in this area. This demonstration confirmed by direct observation the earlier indications of this feature which had previously been inferred indirectly by other means.

The radiometer and scatterometer, designed to measure surface wind speeds, also yielded data which showed that they, too, can be expected to perform well in future EOPAP ocean dynamics missions. Skylab results will be described further later in the discussion.

GEOS-C

GEOS-C, a geodynamic experimental ocean satellite (Figure 1) is scheduled for launch around the end of this year. It is being developed to demonstrate the technical feasibility of new systems and techniques to be used in the Earth and Ocean Physics Applications Program.

The objectives of the GEOS-C Project are to demonstrate the feasibility of obtaining satellite altimeter measurements of the ocean topography which will lead to a better understanding of ocean currents and tides, and to determine the capability of the altimeter to measure sea state, provide a more precise description of the earth's gravity field, and to improve the measurements of the variations in the solid earth's geometry. A satellite-to-satellite tracking (SST) experiment conducted together with ATS-6 will demonstrate a new method for measurement of the earth's gravity field.

The GEOS-C mission orbit parameters are:

Mean Altitude	843 km (500 nm)
Inclination	115°
Eccentricity	0.006 (maximum)
Orbit Period	101.8 minutes

Forty-one investigators or investigator teams were selected from the proposals that were submitted in response to a call for space flight investigations issued in October, 1972. These investigator teams are from government, university, and industrial organizations. Wallops Flight Center, which has the project responsibility for GEOS-C, is in the process of negotiating contracts with the investigators.

Current plans call for the flight of an altimeter in GEOS-C to build upon the successful proof-of-concept tests conducted in Skylab. The GEOS-C altimeter will map the sea surface topography over wide areas of the world's oceans. These findings are expected to give us a global picture of the geoid which will be valuable as an indicator of the structure of the tectonic plates which form the earth's cover, and important to our national defense posture. The synoptic wave height data to flow from this same instrument will aid in developing better models of wave growth and other air-sea interactions which are vital elements in generating our global weather patterns.

SEASAT-A

Introduction

SEASAT-A is the first spacecraft dedicated to a partial meeting of the EOPAP objectives in ocean dynamics. It is an outgrowth of a diversity of scientific and technological work conducted by NASA, the Department of Defense, the Department of Commerce, and several other institutions in both the measurement of the required physical quantities and the implementation of the appropriate sensors on spacecraft and on the ground.

During the feasibility study phase of SEASAT-A, which took place in the first part of 1973, NASA sought the involvement of the "user" community—the agencies and institutions that are the intended users of SEASAT-A data—to help insure that the types and quantity of data to flow from the spacecraft will meet the needs of these organizations in

as satisfactory a manner as possible. The list of active users is large. From the Federal Government it includes:

- Department of Commerce
  - National Oceanic and Atmospheric Administration
  - Maritime Administration
- Department of Defense
  - Defense Mapping Agency
  - Army Corps of Engineers
  - Navy Weather Service Command
  - Office of Naval Research
  - Naval Weapons Laboratory
  - Naval Research Laboratory
  - Naval Oceanographic Office
- Department of Interior
  - Geological Survey
- Department of Transportation
  - Coast Guard
- Atomic Energy Commission
- Environmental Protection Agency
- National Science Foundation
- National Aeronautics and Space Administration
- National Academy of Sciences
- National Academy of Engineering

Institutional users who are active participants are:

- Smithsonian Astrophysical Observatory
- Woods Hole Oceanographic Institution
- Scripps Institution of Oceanography/University of California
- University Institute of Oceanography/City College of New York
- Battelle Institute

From the private sector, the user community includes:

- American Institute of Merchant Shipping
- American Petroleum Institute
- Sea Use Council

The technological heritage of SEASAT-A is broadly based. The predecessor spacecraft and sensors of immediate relevance are: the geodetic satellites GEOS-1 and 2, which led to great refinements in the shape and gravity field of the earth; the successor to this series, GEOS-C, with its precision radar altimeter, due for launch around the end of this year; Skylab and its sensors, especially the Earth Resources Experiments Package, EREP; Apollo 17 and the coherent radar altimeter/imager on board it; ERTS-1 with its Multispectral Scanner; and the Nimbus and ITOS/NOAA series of meteorological satellites with their visible, infrared, and microwave radiometers. SEASAT-A also has a heritage in a myriad of spacecraft subsystems too detailed to be listed here.

Basically, SEASAT-A is a research-oriented program consisting of a spacecraft, precision ground tracking systems, and data processing and modeling capabilities that will address both scientific and applications problems in ocean surface dynamics. Its strong suit is in an array of active radar and passive microwave and infrared instruments that give it the capability of observing the oceans on a day/night, near-all-weather basis. It is this group of sensors that allows SEASAT-A to make quantitative measurements of oceanic, atmospheric, and geodetic parameters not only in clear weather, but under wind and wave conditions perhaps approaching hurricane force, as well as over regions lying under persistent cloud cover. How this is accomplished is best appreciated after the system configuration has been laid out.

Configuration and Mission

Two groups are presently studying SEASAT-A, the NASA Wallops Flight Center, managing the Applied Physics Laboratory of The Johns Hopkins University, and the Jet Propulsion Laboratory of the California Institute of Technology. Figure 2 depicts a possible spacecraft design for SEASAT-A. The prominent features on each design are the microwave antennas and, of course, the solar cell panels. The spacecraft is three-axis stabilized to point toward the vertical to within ±0.5°.

The mission profile for SEASAT-A is tentatively as follows: lifetime, one year minimum; orbit, approximately 800 km altitude at an inclination of 108° (retrograde); eccentricity, less than 0.006, for a nearly circular orbit; period, 100 minutes, resulting in 14 1/2 orbits per day. This orbit is non-sun-synchronous and will precess through a day/night cycle in approximately four and one-half months. Its ground track for one day is shown on Figure 3; as can be seen, it spans almost all of the unfrozen oceans of the world from the Antarctic to the Alaskan North Slope and the Canadian archipelago. The orbit is also optimum for fine-grained mapping of the geoid over the open ocean.

Instruments and Sensors

Each of the sensors proposed for SEASAT-A has predecessors which have been successfully flown on both aircraft and spacecraft. Good-to-excellent assessments of the capabilities of these prototypes are in hand for wind and wave conditions approaching gale force. Enough is known of their theory of operation to make reasonable estimates of their performance under other more severe environmental conditions. The selection of instruments was made in order to determine ocean surface conditions in accordance with user data requirements set forth during NASA-sponsored meetings in early 1973. The sensors form a set of integrated, interactive, and mutually supporting devices whose simultaneous use brings about a genuinely synergistic effect wherein the total information derived from the sensor package is greater than the sum of the individual outputs. While it has not been possible to meet the user data requirements in their totality because of limitations on system performance, the five sensors described below constitute a large first step toward an optimum configuration.

Compressed Pulse Radar Altimeter (CPRA) —The CPRA has two distinct functions: to measure the altitude between the spacecraft and the ocean surface to a root-mean-square precision near ±10 cm, and to determine significant wave heights along the subsatellite path. The altitude, when blended together with accurate orbit determinations, may be used to decipher the topography of the sea surface including spatial variations in the geoid and time variations due to ocean dynamics.

A current NASA estimate of the geoid in the western Atlantic, as derived from satellite tracking data and surface gravity measurements, is given in Figure 4. The figure shows the geoid, that is, the theoretical elevations and depressions of the motionless ocean surface due to gravity, with contours of constant height given in meters, relative to an elliptical earth.

The prominent surface depression due to the deep ocean trench north of Puerto Rico has been observed by different methods, the Skylab radar altimeter, S-193, being the first to give a continuous direct measurement of the sea surface topography. Figure 5 schematically shows a Skylab track over the trench; the 11 km "footprint" of the S-193 altimeter; a depth profile along the track; and an altimeter trace of the overlying ocean surface and island topography. The measurement has been repeated by the Skylab altimeter with near-identical results. The spacecraft measurements bear out both other observations and detailed calculations which indicate that the ocean surface is depressed by 15-20 m over a 100- to 150-km distance north of Puerto Rico, due to the gravity anomaly associated with the trench. Anomalies which are elevations rather than depressions have also been observed from Skylab. These are due to seamounts, plateaus, and the mid-Atlantic Ridge. Thus, the whole foundation of precision geoidal measurements via spacecraft altimetry seems to be on a reasonable theoretical and observational footing. The problems are to extend it globally and increase the precision.

The Skylab altimeter has a one-meter altitude precision, which nearly precludes it from seeing the much smaller topographic departures from the geoid that are due to ocean dynamics effects. Such time-varying features as intense currents, tides, wind pile-up, storm surges, and tsunamis are in principle observable with an altimeter having sub-meter precision by measuring sea surface slopes relative to the geoid. For currents, the slope of the surface is proportional to the surface speed. In fact, it was the prospect of measuring ocean surface currents globally, using altimetry and precise orbit determination, that initially brought members of the oceanographic community into the geodesy program. However, the topographic variations due to even intense systems such as the Gulf Stream or the Kuroshio off Japan are quite small compared to the gravity-caused geoidal undulations, as Figure 6 indicates. In this illustration, seasonally averaged density measurements of the Gulf Stream have been used to calculate a departure of the sea surface from the geoid amounting to about 110 cm across the northwestern boundary due to the current system with surface speeds of 150-250 cm/sec moving on a rotating earth. This is the source of the well-known "sailing-uphill-while-crossing-the-Gulf-Stream" statements. These topographic variations have never been measured directly; nevertheless, preliminary data from Skylab suggest the Gulf Stream boundary is barely detectable in the altimetric traces. By extending these measurements to the sub-meter level with GEOS-C, and further refining them iteratively with SEASAT-A data, it should be possible to demonstrate the ability to determine ocean surface currents ranging upwards from about two thirds of a meter per second and, more importantly, to map their considerable changes in time and space. When appended to other spacecraft-derived data, such as infrared images, such measurements would in time allow a mapping of the distribution and speed of one or more of the stronger ocean currents lying between the intermediate equatorial belt and the ice-covered polar regions on a timely enough basis to be useful for a variety of scientific and commercial purposes.

The same altimeter precision of ±10 cm would, together with knowledge of the satellite altitude of comparable accuracy, allow measurements of deep ocean tides, whose range is zero to perhaps one meter; the piling-up of water along a coastline by steady winds (about one meter elevation) or by strong winds—the storm surge—(up to 10 meters); and the height and distribution of tsunamis, the long, fast waves caused by earthquakes (heights of about one-half meter in the open ocean). However, storm surges and tsunamis cannot be routinely measured because they require the satellite to be overhead as they occur.

The determination of these small departures with a precise altimeter will necessitate concomitant advances in the science of orbital dynamics and in the technology of satellite tracking. The same geoidal model used as a reference for ocean dynamical features, when converted to the gravity field and extended to satellite altitudes, will assist in arriving at orbit measurements having sub-meter accuracies in the vertical coordinate. Highly precise metric techniques using pulsed lasers, radars, and doppler receivers for tracking will be necessary for the determination and updating of the spacecraft orbit.

The second function of the SEASAT-A compressed pulse radar altimeter mentioned earlier, that is the measurement of significant (or statistically averaged) wave height, is also required in order to reach a 10-cm precision in altitude. In addition, the wave height is a valuable commodity in its own right, since it can be used along with surface wind measurements to make world-wide sea state forecasts. The principle of the measurement is shown in Figure 7. A short pulse reflected from a rough sea will be broadened by the

various reflecting levels which the waves give rise to. The broadened shape of the echo contains wave height information, the rougher seas returning the longer the echos. Aircraft flights have shown this technique to work in low to moderate seas, as have Skylab data. On SEASAT-A, wave heights from one to above 20 meters should be measurable along the subsatellite track on a near-all-weather basis.

Coherent Imaging Radar (CIR)—The required extension of wave information will be made by using a coherent imaging radar to obtain images of the ocean on a sampled basis. Such a radar can function through clouds and moderate rain to yield wave patterns near shorelines and in storms, and can see waves whose length is greater than about 50 m. It can also provide high resolution pictures of ice, oil spills, current patterns, and similar features. Computations can be performed on the radar data to yield a quantity called the wave directional spectrum which gives the relative distribution of wave energy among different wavelengths traveling in various directions. This, together with the surface wind velocity, is the fundamental information needed in forecasting of wave conditions on the ocean.

Figure 8 illustrates two trains of waves off Kayak Island, Alaska, one of 150-m and the other of 60-m wavelength, taken from the NASA Convair 990 aircraft with the Jet Propulsion Laboratory imaging radar. The waves are being refracted and shortened by shoal water as they approach the island visible on the left-hand side. Also on the lower left and center of the figure is a directional spectrum computed for the relatively uniform part of the wave train to the right of the image. Distance from the center of the spectrum corresponds to increasing wave frequency, angle to direction of propagation, and intensity to wave energy.

The data rate from an imaging radar is high, and judicious use must be made of the device. Nevertheless, it should be possible to sample wave spectra over patches of ocean of sufficient size and density to obtain global data on sea conditions. Near the NASA receiving sites along the U.S. coasts, more generous quantities of imagery will be taken and studies of storm wave patterns near potential offshore nuclear power plant sites, deep water oil ports, harbors, and breakwaters will be made. Over the Northwest Passage and the Great Lakes, a demonstration of real-time mapping of ice leads and open water will be made as an aid to navigation through those straits and inland seas.

The imaging radar has several experimental modes, including an altimeter function and a wind scatterometer mode. The latter will be described below in conjunction with another sensor.

Microwave Wind Scatterometer (MWS)—The third radar system is a microwave scatterometer, intended to measure surface wind speed and direction by sensing the small capillary waves induced by the wind over the ocean. Previous aircraft experience and recent Skylab data taken over the Pacific hurricane *Ava* in June 1973 indicate this sensor is useful in winds approaching 25 m/s. It is expected to yield speeds with an error of ±2 m/s and directions to ±20°. Figure 9 illustrates *Ava* as taken from the environmental satellite NOAA-2 on the left; on the right are graphs from Skylab S-193 showing radar scattering, radiometer temperature, and, in the upper right-hand corner, wind speed. The peak wind of 45 knots (22 m/s) obtained from the scatterometer was observed some distance from the eyewall, which the sensor could not view because of look-angle constraints.

In the SEASAT-A configuration, the output of the scatterometer will be measurements of lower wind speeds and directions taken over two 450-km-wide swaths equally displaced about nadir by 300 km. In 12 hours, these swaths map out a quilt-like pattern of areas over the portion of the

oceans between 72° north and south latitude with enough density of observations so that an essentially complete chart of surface winds will be obtained.

It is anticipated that an experimental variation of this instrument termed the Wave Spectrometer may be operated simultaneously with the MWS as an alternative, less complicated and less complete method of obtaining wave directional spectra along a 300-km-wide swath about nadir.

Scanning Multifrequency Microwave Radiometer (SMMR) — The SMMR is a passive, nonradiating microwave device, in contrast to the three previous sensors. It simultaneously senses the microwave energy emitted by and reflected from the ocean, ice, and atmosphere. In order to separate the various contributions to the signal from these sources, several microwave frequencies are used, each being chosen for maximum sensitivity to one of those geophysical parameters. The scanning feature will allow low-resolution images of objects along its line of sight to be constructed from the signals received.

Figure 10 is one such low-resolution image made at a microwave frequency of 35 gigahertz, using the Nimbus-5 Electronically Scanning Microwave Radiometer (ESMR). While this instrument was adjusted primarily for viewing ice, it nevertheless shows rainfall and the near-permanent cloud cover over the intertropical convergence zone (ITCZ) just north of the equator.

The SEASAT-A instrument will be a device considerably improved over the ESMR now on Nimbus-5. It will be optimized for viewing the sea by scanning at the proper angles over a swath width of about 900 km about nadir. The resolution, or instantaneous field of view (IFOV), will vary between 15 and 100 km, depending on frequency.

The functions of the SMMR are severalfold. It is first a wind speed instrument that senses the increase in emitted microwave energy due to roughness, foam, and streaks on the ocean caused when higher wind speeds create wave breaking and whitecaps. The estimated observable range of speeds is from about 10 to perhaps 50 m/s, or 20 to 100 knots, but the upper limit has yet to be firmly established. Thus, the range of speeds measurable from SEASAT should be extended by SMMR from the 25 m/s limit of the scatterometer up toward hurricane force winds. Secondly, it appears capable of measuring sea surface temperature with an accuracy of 1.5°–2°C, even through light clouds, where present infrared devices are useless, such as over the ITCZ. Thirdly, the other frequencies are used for determining atmospheric liquid water and water vapor content, quantities that are needed in models of oceanic and atmospheric boundary layer processes as well as for important corrections to the precision altimeter measurements. Ice fields and cover will also be observed with low resolution by the SMMR.

Maps of higher speed ocean surface winds, temperatures, and overlying atmospheric water content will be the output of the SMMR. These maps will, of course, be blended with the wind data from the Microwave Wind Scatterometer to yield a global, quantitative chart of wind speed wherever it is below essentially hurricane force. The measurements will be equivalent to some 20,000 ship reports a day. When combined with available ship and buoy surface information on wind and pressure, it becomes possible to compute the atmospheric pressure field over the entire ocean, except perhaps near severe storms; this will also be true in the data-sparse southern hemisphere. Such results should help to improve the 24-hour weather forecasts substantially, perhaps making them extensible to two or three days. This improved predictive capability for winds implies an approximately equal improvement in forecasting waves, especially when assisted by the data on the initial state of the sea obtained from the radar altimeter and imager.

Infrared Radiometer (IRR)—The purpose of this sensor is to provide images of thermal infrared emission from ocean, coastal, and atmospheric features, which will aid in interpreting the measurements from the other four microwave instruments. In addition, it will have atmospheric correction channels that will allow one to deduce temperatures from the imagery with a precision of better than 1°C in clear air. The device will be similar to scanning radiometers flown on Nimbus and ITOS/NOAA. Figure 11 is an example of imagery taken from the NOAA-2 Very High Resolution Radiometer over the southeastern United States and clearly shows the Gulf Stream off the coast as a dark band of water, as well as the Gulf of Mexico Loop Current, a time-varying feature that apparently profoundly affects the fisheries and the weather in that sea.

A word on the measurement of sea surface temperature is in order here. This parameter is actually of considerable importance in oceanic and atmospheric processes, since it results from the absorption of that prime mover, solar energy, by the sea. For instance, the difference between active and inactive hurricane seasons may be due to just 2-3°C in water temperature in hurricane gestation areas. Ocean temperature is a major factor determining the tone of weather and climate in many coastal regions of the world. Maps of sea surface temperature are very useful for tracing current systems such as the Gulf Stream, especially in the winter months. Furthermore, open-ocean fish such as tuna tend to swim along lines of constant temperature at certain times during their excursions, and a knowledge of temperature can assist in their location. Thus, sea surface temperature offers a clue in several important areas of interest.

The Total System

As has been suggested above, these sensors separately provide data which, when used jointly, enhance the interpretation of the total set. Figure 12 shows the ocean coverage provided by the devices. The informational output of the instrument complement will fall into three classes. The first will be measurements of wave height, wave directional spectrum, and surface wind speed and direction over the global ocean with a repeat time of 12 to 36 hours, on a somewhat uneven grid that is at least as fine as about eight degrees in most parts of the world. The second class will be sea surface topography from which currents, tides, and other similar features may be deduced in selected regions over time scales of days or weeks. The third class is high resolution imagery, both radar and infrared, made over selected areas at specified times, on selected time and space scales.

The interrelationships between these several classes of data are suggested in Figure 13, which illustrates the complex nature of the contribution that each sensor makes to the geophysical parameters being measured. The figure indicates the importance of carrying the full sensor complement in order to achieve the measurement objectives. The flow of the EOPAP ocean dynamics program in terms of the measurement objectives of the sequence of flight missions and their instrument complements is summarized in Tables I through III.

SEASAT-A is thus an integrated observatory addressing the objectives discussed at the beginning of this paper. The advances expected from SEASAT-A in the context of its predecessor flight missions in the EOPAP ocean dynamics program are indicated in Table IV. The local region measurement objectives listed there are expected to be met, for example, in the Western North Atlantic quadrangle area defined by Goddard, Bermuda, Grand Turk, and Cape Kennedy where accurate laser trackers will pin down the orbital height of SEASAT-A. The deep ocean tide aims correspond to the use of a year's span of data providing appropriate coverage.

The requirements set forth by the users are indicated in Table V. Table VI outlines the capabilities of the SEASAT-A spacecraft system from the standpoint of its ability to meet these requirements. Not all of the desiderata have been met. In particular, the requirements of a generally operational character will probably demand more than one spacecraft. Thus, the request for continuous coverage of wind and waves with an update every 12 hours, the desire for 10-km surface resolution on the SMMR channels, and the requirement for 1/4°-all-weather temperature have been impossible to achieve in this SEASAT-A mission. Neither does it appear feasible to reach the overall ±10-cm accuracy in geoid, altimeter, and orbit determination needed to reduce the ultimate errors in current measurements to the level of 20 cm/sec. These must await follow-on systems.

These data will nevertheless be highly valuable both for research purposes and for demonstrations of near-operational uses in marine and weather forecasting. The program plan calls for assembling all of the data in compatible format through a command and control center at the Goddard Space Flight Center, reducing and interpreting them as geophysical quantities, and disseminating them to research scientists. In addition, on a few occasions during the life of the satellite, a real-time, quasi-operational exercise will be conducted in which the wind/wave/imagery information will be sent out on communications channels to users such as NOAA's National Meteorological Center or the DOD Fleet Numerical Weather Center within some three hours. Another exercise visualized is one in which near-real-time radar images of the ice fields along part of the Northwest Passage are obtained and estimates made of their usefulness to real or hypothetical ship passages.

An important element in interpreting the SEASAT-A data and extending their utility will be the considerable body of data on the oceans and atmosphere available from other sources. The environmental/meteorological satellites are one such obvious source for marine and weather data, as are ships, buoys, and transoceanic aircraft. In the case of ocean wave forecasts, a land-based, high-frequency skywave radar that is intended for detailed monitoring of wave spectra near the continental United States is expected to be in service. Its fine-grained data will complement nicely the more coarsely spaced open ocean wave spectral data from SEASAT-A. Similarly, correlative data on currents, tides, the geoid, and the other parameters of interest will be amalgamated with the SEASAT-A data by individual researchers interested in specific problems.

SCIENTIFIC RESEARCH

In addition to being an applications satellite, SEASAT-A will be an important research tool in several areas of geophysics. The following list of scientific problems that it can address is representative rather than exhaustive.

Oceanography—The mapping of major ocean currents and their time and space variations in selected regions will be achievable by a combination of infrared imagery to yield positions (see Figure 11), and precision altimetry to give estimates of surface speeds. Figure 14 illustrates meanders of the Gulf Stream off the northeastern U.S., as delineated during three months of ship measurements in 1965 (*Hansen,* 1970). It also shows several orbits over the stream which demonstrate the sampling density that may be obtained from the satellite altimeter (*Siry,* 1973b). Figure 15 illustrates global, averaged ocean current systems. This idealized picture differs dramatically from the actual one, as a comparison of the Gulf Stream in Figures 14 and 15 shows. The SEASAT program should refine this picture considerably.

Global deep sea tides should be extractable from altimetry measurements with errors of

perhaps a few tens of centimeters after a year of data-taking. In contrast, only a few dozen measurements of open ocean tides presently exist.

The sensing by the altimeter of a tsunami in the Pacific may be possible if one or more of these earthquake-caused waves occur during the lifetime of the satellite. The information obtained may assist in determining the energy content of the tsunami and help reduce the problem of overwarning that now exists. However, an operational warning system cannot be predicated on the basis of satellite altimetry.

Ice dynamics can be studied with repeated radar imagery taken in the polar regions. The size and extent of leads and cracks establish the heat exchange between air and water which is key to much of the weather in those regions.

The generation, spatial distribution, and radiation of waves by storms and hurricanes may be investigated with radar imagery. Using detailed wave spectra, wave-wave interaction may be studied as a process that cascades energy from short to long waves, thus leading to high sea states. Little is known quantitatively about the surface wave regime on continental shelves under severe storm conditions. Similarly, interactions of storm surf with shorelines and coastal structures can be observed during bad weather.

Oceanographers have never been able to gain the overview of their domain required to understand synoptic or planetary scale events in the sea. SEASAT-A promises to provide a very important vantage point for that view.

Boundary Layer Meteorology—The greatly increased knowledge of the surface temperature and wind fields over the oceans will aid in understanding large-scale atmospheric circulation and air/sea heat exchange. The effects of sea temperature on hurricane growth, on jet stream deflection, and on global climatology may be illuminated by these measurements. Pole-ward transport of heat by oceanic currents can be assessed more accurately and the effect on the overall heat balance assayed.

Geodetic Science—The prime geodetic output of SEASAT-A will be a precise, fine-scale equipotential surface, or geoid, over the ocean. This figure of the earth may be used to determine gravimetric deflections of the vertical at sea. Near land, the latter can be used to check the accuracy of the new North American Datum. Gravity anomalies due to large underwater features such as seamounts and trenches may also be observed. The discrepancies between spirit leveling and sea level measurements along the coasts may be resolved by the precise knowledge of sea surface topography.

The improved gravity field should lead to more accurate satellite orbital determination. The polar wandering and other non-rigid earth motions may then be measured more readily using orbit analysis and accurate tracking.

Geophysical discipline studies expected to benefit from results of the EOPAP ocean dynamics program and, in particular, from SEASAT-A findings are indicated in Table VII.

Engineering Science—A high-technology system such as a spacecraft always brings along with it a number of important developments in technology and engineering science. While it is difficult to specify exactly what the yield of SEASAT-A in this regard will be, it is safe to speculate that, in areas of short-pulse and coherent radars, in tracking technology, and perhaps in data handling and dissemination, significant advances are expected. It is likely that other technologies will be upgraded during the program as well.

APPLICATIONS

In addition to being of considerable interest to a number of scientific disciplines, the SEASAT-A program will yield data whose application to problems in several sectors of public and private concern will yield sizable benefits. These can be grouped under (1)

protection of life and property, (2) economic benefits, and (3) national defense posture. In almost all of these cases, the spacecraft data is only a part, albeit usually an important part, of the total information needed to solve the applications problem.

Protection of Life and Property—Improvements in navigation and safety at sea may be achieved by the better forecasts of high seas obtained from SEASAT-A global-scale wind and wave data. Navigation through ice in passages can be demonstrated on an experimental basis using radar images of limited areas. Better knowledge of current systems in the northwestern Atlantic will aid in forecasting movement of icebergs across shipping lanes. Such information will undoubtedly lead to decreases in the loss rates of men, ships, and cargo, although not on the scale possible with an ultimate, operational ocean monitoring system.

Warning of hazards due to weather can be made more accurate and timely through the same general body of data. Quantitative measures of winds up to near-hurricane force will lead to more accurate predictions of storm landfall and storm surge forecasts. These measurements, when melded together with other meteorological data, will aid in extending the one-day general weather forecast towards a scale of a few days.

Economic Benefits—In principle, large economies are possible for activities utilizing SEASAT-A-derived information directly or indirectly. In the area of maritime operations, minimum-time routing of transoceanic shipping around storms can save 12 to 24 hours of ship time on a single crossing, which, when translated into savings at the rate of $10,000 a ship-day, amounts to eight figure numbers of dollars per year, world-wide. Reduced cargo breakage and insurance rates and improved harbor and canal scheduling would add to those savings. Wave forecasts will also aid in scheduling of the critical processes of deploying and operating floating oil drilling platforms. Similarly, measurements of wave spectra on the continental shelves under storm conditions are necessary for the location and design of offshore structures such as floating nuclear power plants and deep water oil ports. Better hydrodynamic design of ships will also result from wave spectral data for the open ocean.

In a slightly different vein, geodetic measurements will ultimately translate into improved navigation, positioning and charting techniques, and location control at offshore positions.

The utilization of living and non-living marine resources is also enhanced by knowledge of currents, temperatures, and waves. Assessment of biological productivity and location of potential fisheries depend in part on the former two parameters, while ocean dredging and mining of minerals, sand and gravel require wave data and forecasts for efficient operation. The impact of pollutants on the ocean can be estimated more accurately by knowing how currents and winds advect material dumped into the sea. Improvements in shoreline protection and assessments of jetty and harbor construction may also be had.

National Defense Posture—The Nation's defenses will be assisted by improved environmental forecasts and geoidal models. Various Department of Defense missions are likely to be positively affected by the range of information derived from SEASAT-A data.

Table VIII summarizes the discussion on benefits. As with the science problems, the list is representative and can be extended.

A benefit/cost study is being conducted by NASA with the participation of many of the users listed previously. Preliminary estimates based on the value to operational users of the wind and wave data alone indicate positive results.

Projections for the Future

After the initiation of the final execution phase later this year, work will commence that should see the spacecraft launched in 1978. Data taking will begin immediately. After functional check-out and calibration of the sensor systems is complete, some time will be spent on assessment of the capabilities of the instruments. High wind and wave calibrations previously derived through participation of the SEASAT-A instrument scientists in exercises such as the North Pacific (NORPAC) Experiment will be used in this phase. Comparison of the spacecraft measurements with "sea truth" obtained simultaneously with the satellite overpass will establish the validity of the measurements. Data will be made available to other government agencies and to institutions in the private sector which will conduct their own investigations.

SEASAT-A promises to be an exceptionally useful and productive program. It should have a large impact on earth science, and on a community of users and the general populace, advancing the welfare significantly.

REFERENCES

Hansen, Donald V., "Deep Sea Research," *17*, 495-511, 1970.

NASA, "The Terrestrial Environment: Solid Earth and Ocean Physics: Application of Space and Astronomic Techniques," August 1969.

NASA Earth and Ocean Physics Applications Program, September 1972.

Siry, Joseph W., "A Geopause Satellite System Concept," Space Science Reviews, *14*, 314-341, 1973a.

Siry, Joseph W., "Gravimetric Geodesy and Sea Surface Topography Studies by Means of Satellite-to-Satellite Tracking and Satellite Altimetry," Geophys. J. R. Astr. Soc., in press, 1973b.

TABLE I—NASA EARTH AND OCEAN PHYSICS APPLICATIONS PROGRAM (EOPAP)
OCEAN DYNAMICS PROGRAM

	Altimeter	Imaging Radar	Scatterometer	Microwave Radiometer	Infrared Imager
Waves					
Heights	X				
Directional Spectra		X			
Patterns		X			
Surface Winds					
Low Speed			X		
High Speed				X	
Ocean Temperatures					X
Under Clouds				X	
Ice Leads		X			
Deep Ocean Tides	X				
Currents					
Topography	X				
Patterns					X
Ocean Geoid					
Fine Structure	X				

TABLE II—NASA OCEAN DYNAMICS PROGRAM

	Altimeter	Imaging Radar	Scatterometer	Microwave Radiometer	Infrared Imager
1973 SKYLAB Exploratory Experiments	X		X	X	
1974 GEOS-C Global Surveys	X				
1978 SEASAT-A Global Monitoring	X	X	X	X	X

TABLE III–NASA EARTH AND OCEAN PHYSICS APPLICATIONS PROGRAM (EOPAP) OCEAN DYNAMICS PROGRAM

	1973 SKYLAB Exploratory Experiments	1974 GEOS-C Global Surveys	1978 SEASAT-A Global Monitoring
Waves			
Heights	X	X	X
Directional Spectra			X
Patterns			X
Surface Winds	X		X
Ocean Temperatures Under Clouds	X		X
Ice Leads			X
Deep Ocean Tides		X	X
Current Topography			X
Ocean Geoid Fine Structure	X	X	X

TABLE IV–NASA EARTH AND OCEAN PHYSICS APPLICATIONS PROGRAM (EOPAP) OCEAN DYNAMICS PROGRAM

Phenomena Observed	Current Sources	Measurement Objectives		
		Region	GEOS-C	SEASAT-A
Waves				
Heights	Partial, Nonuniform Ship Coverage	Global	25% 4-10M	0.5M or 10% 1-20M
Directional Spectra and Patterns	Negligible	Global Sampling		50M, 10% 10°
Surface Winds	Partial, Nonuniform Ship Coverage	Global		2 M/S or 10% 20°
Ocean Temperatures Under Clouds	Partial, Nonuniform Ship Coverage	Global		1.5° - 2°
Ice Leads	Negligible	Global Sampling		50M, 10%
Deep Ocean Tides	Sparse Deep Ocean Tide Gage Coverage	Global Local	1 M 1/3 M	1/3 M 0.1 M
Current Topography	Negligible	Local		1/3 M
Ocean Geoid Fine Structure	Partial, Nonuniform Ship Coverage	Global Local	3-5 M,5° 1 M	1-2M,1° 1/3 M

TABLE V--USER REQUIREMENTS AND INSTRUMENTS

Physical Parameters	Range	Precision Accuracy	Resolution/ IFOV	Spatial Grid	Update Free COV	Sensors
1. Wave Height, $H_{1/3}$ (r, θ, t)	1. 0.5-20 m	± 0.5 m or 20%	20 km	50 km	12 Hr Global	■ Compressed Pulse Radar Altimeter
2. Wave Directional Spectrum, $S(k_r, k_e, r, \theta, t)$	2. 0.5-20 m 0-360°	± 0.5 m or 20% $\Theta \pm 10°$ λ 20%	$\lambda > 50$ m	50 km	12 Hr Global	■ Synthetic Aperture Coherent Imaging Radar
3. Surface Wind Velocity, $W(r, \theta, t)$	3. 0-50 m/s 0-360°	± 2 m/s or 20% $\Theta \pm 20°$	25-50 km	25-100 km	12 Hr Global	■ Scanning Microwave Radiometer (High Winds) Scanning Microwave Scatterometer (Low Winds)
4. Sea Surface Topography Major Currents	4. 10-200 cm Per 10 km	± 10 cm	10 km	10 km Swath	2-5 Day Local	■ Compressed Pulse Radar Altimeter
Tides, $\zeta(r, \theta, t)$	0-200 cm	± 10 cm	10 km	1° x 1°	Global	■ Coherent Altimeter
Storm Surge, $\zeta(r, \theta, t)$	1-10 m	± 50 cm	10 km	10 km Swath	Real Time Local	
Tsunami, $\zeta(r, \theta, t)$	10 cm-10 m	± 10 cm	10 km	10 km Swath	Real Time Local	
Geoid Elevations, $h(r, \theta)$	10 cm-20 km	± 10 cm	10 km	1° x 1°	Global	
5. Sea Surface Temperature, $T(r, \theta, t)$	5. −2° to 35°C All Weather	± 0.5°C	0.5-100 km	Continuous	12 Hr Global	■ Scanning Microwave Radiometer ■ IR Radiometer
6. Ocean Features	6. High Resolution		10-100 m	Images	Local	Imaging Radar
Current Boundaries	Medium Resolution		1-10 km	Images	Synoptic	IR Radiometer
Ice, Land	Low Resolution		10-100 km	Continuous	Global	μ W Radiometer

CAPABILITY OF SEASAT-A IN MEETING USER REQUIREMENTS

PHYSICAL PARAMETER	INSTRUMENTS	RANGE	PRECISION	RESOLUTION OR IFOV	TOTAL FOV	COMMENTS
Wave Height, $H_{1/3}(x,y)$	Pulse Altimeter	1.0 – 20 m	±0.5 m or ±10%	2x7 km spot	2-km swath	along subsatellite track only
Directional Wave Spectrum $S(\lambda,\Theta,x,y)$	Imaging Radar (2-D transform)	S: unknown λ: 50-1000 m Θ: 0-360	S: --- λ: ±10% Θ: ±10°	50-m resolution	10 x 10 km squares	global samples at 500-km intervals
Surface Wind Field, U (x,y)	Scatterometer	U: 3-25 m/s Θ: 0-360	±2 m/s, ±10% ±20°	≤ 50 km spot	two 450-km swaths	global, 36 hrs (low speeds)
	μW Radiometer	U: 10-50 m/s Θ: unknown	±2 m/s, ±10% --	≤ 100 km spot	900-km swath about nadir	global, 36 hrs (high speeds)
Surface Temperature Field, $T(x,y)$	IR Radiometer	-2° to +35°C	±¼° - 1°C	1-7 km IFOV	1500-km swath about nadir	global, 36 hrs (clear air only)
	μW Radiometer	0° to 35°C	±1.5°C	100 km spot	900-km swath about nadir	global, 36 hrs (clouds & lt. rain)
Geoidal Heights, $h(x,y)$ (above reference ellipsoid)	Pulse Altimeter	7 cm - 200 m	7 cm	2x7 km spot	18-km spacing along equator	sampled throughout one year
Sea Surface Topography, $\zeta(x,y)$ (departures from geoid)	Pulse Altimeter	7 cm - 10 m	±7 cm	2x7 km spot	2-km swath	along subsatellite track only
Oceanic, Coastal, & Atmospheric Features (Patterns of waves, temp., currents, ice, oil, land clouds, atmospheric water content)	Imaging Radar	high resolution	all weather	25 m	100 km	sampled direct or stored images
	IR Radiometer	high resolution	clear air	1-7 km	1500-km swath	broadly sampled images
	μW Radiometer	low resolution	all weather	15-100 km	900-km swath	global images

TABLE VII–NASA EARTH AND OCEAN PHYSICS APPLICATIONS PROGRAM (EOPAP)
OCEAN DYNAMICS PROGRAM

Phenomena Observed	Related Discipline Studies
Waves	
Heights	Currents, Meanders, Eddies
Directional Spectra	Air-Sea Interactions, Meteorology, Climatology
Patterns	Land-Sea Interactions, Coastal Processes
Surface Winds	Air-Sea Interactions, Meteorology, Climatology
Ocean Temperatures Under Clouds	Inter-Tropical Convergence Zone, Southern Ocean, Hurricanes, Storms Air-Sea Interactions, Meteorology, Climatology
Ice Leads	Heat Transfer, Air-Sea Interactions, Meteorology, Climatology
Deep Ocean Tides	Dissipations, Solid-Earth Tidal Interactions
Current Topography	Meanders, Eddies, Circulations, Climatology
Ocean Geoid Fine Structure	Lithosphere & Asthenosphere Structure and Dynamics

TABLE VIII—BENEFITS DERIVED FROM SEASAT-A DATA

General	Specific
Advancement of Knowledge	Oceanographic, Meteorological, Geodetic and Engineering Science
Protection of Life and Property	
Navigation and Safety at Sea	Prediction of High Seas, Adverse Currents Navigation through Ice Fields More Precise Iceberg Warnings Decreased Loss of Men and Ships
Warning of Natural Hazards	More Accurate, Longer-Term Weather Forecasts Improved Warnings of Storms and Surges Decreased Tsunami False Alarm Rate
Economic Benefits to the Nation	
Maritime Operations	Optimum Ship Routing and Scheduling Reduced Loss of Oil Drilling Rigs Improved Design of Offshore Structures Improved Ship Design Improved Mapping, Charting, and Geodesy
Utilization of Ocean Resources	Assessment of Biological Productivity Location of Potential Fisheries Enhanced Extraction of Oil, Sand, Minerals
Environmental Impact	Dispersal of Pollutants and Foreign Substances Improvement in Shoreline Protection
National Defense Posture	Improved Environmental Forecasts More Precise Geoidal Model Enhancement of Other DOD Missions

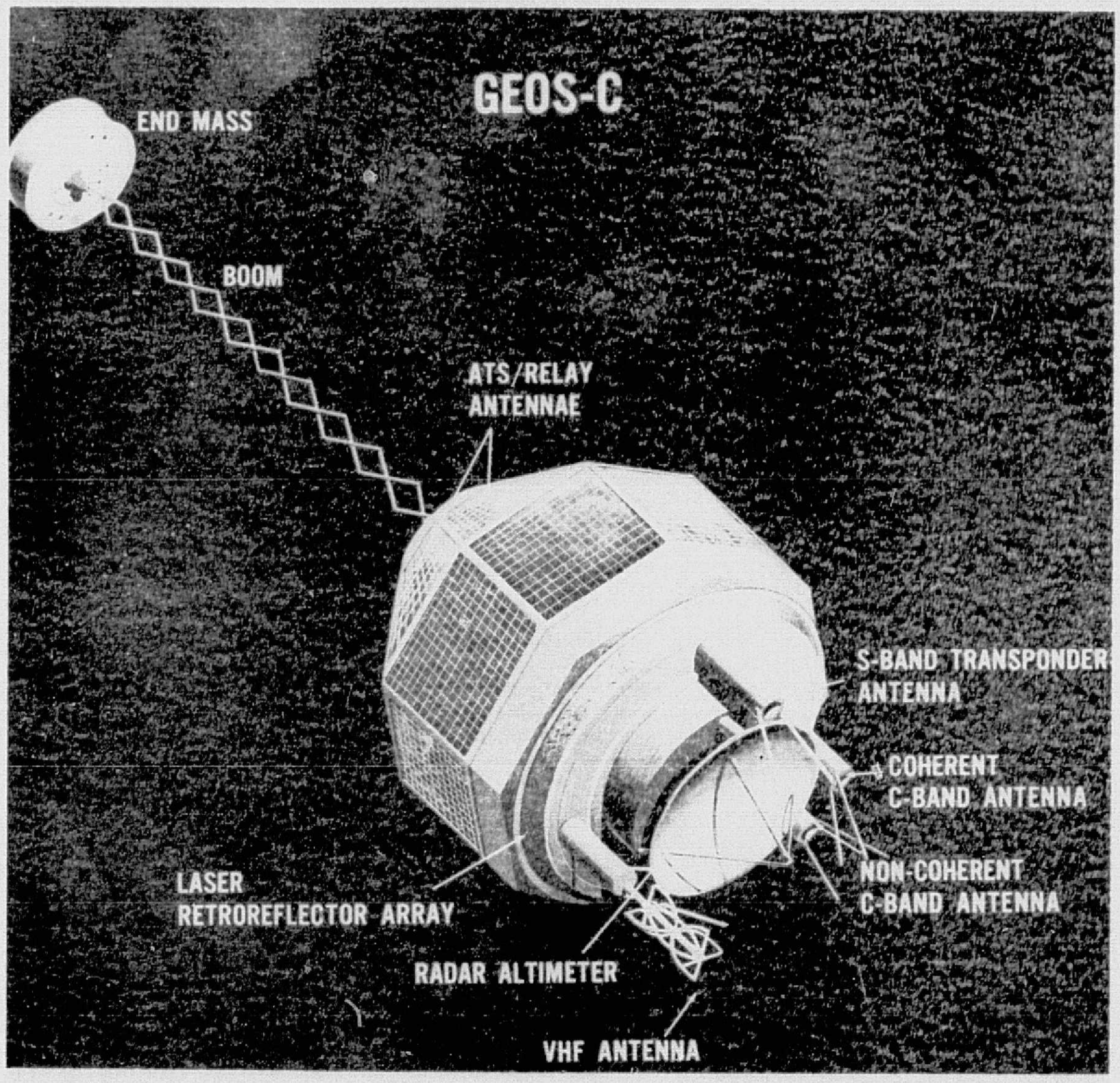


Figure 1. GEOS-C

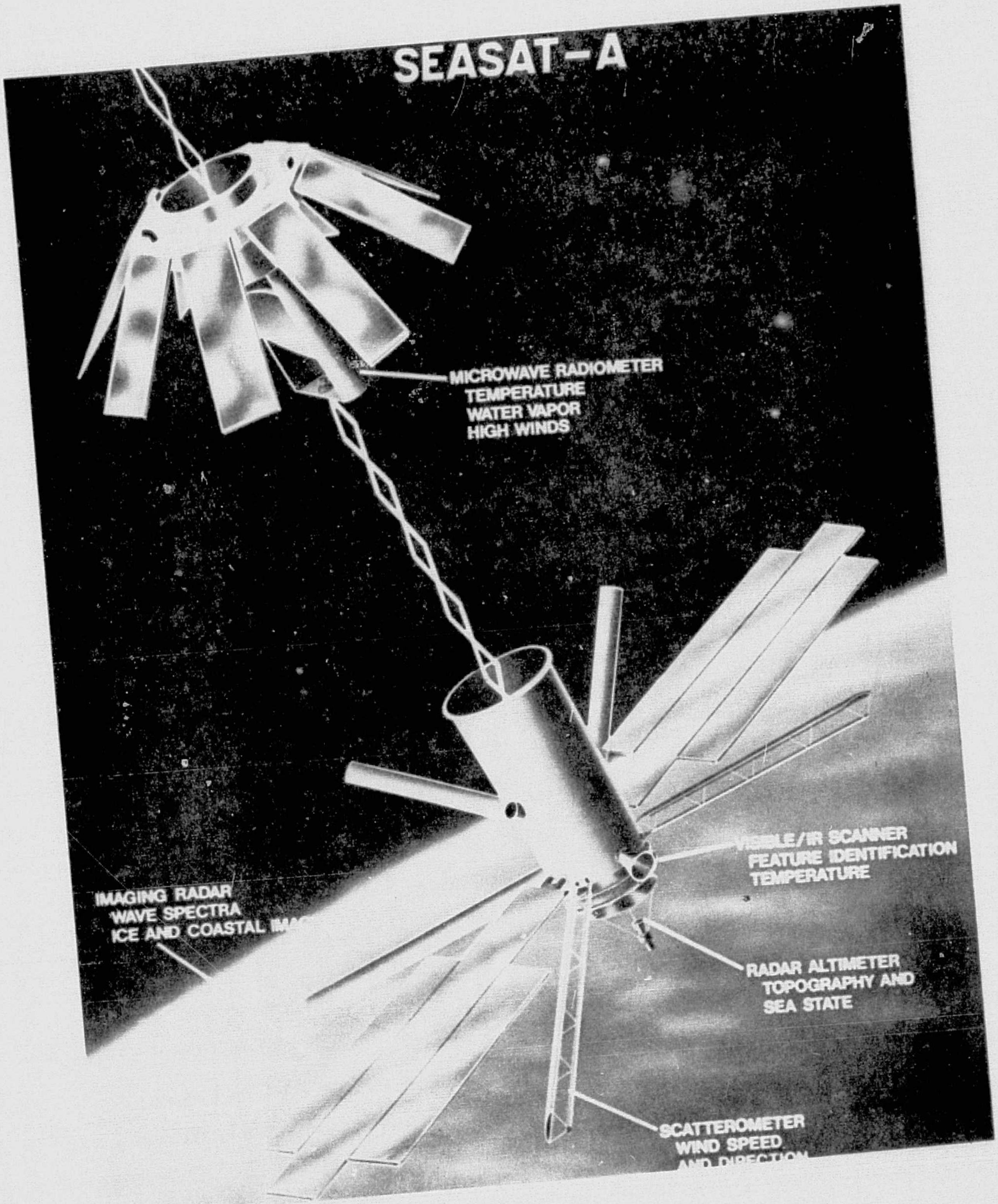


Figure 2.–SEASAT-A

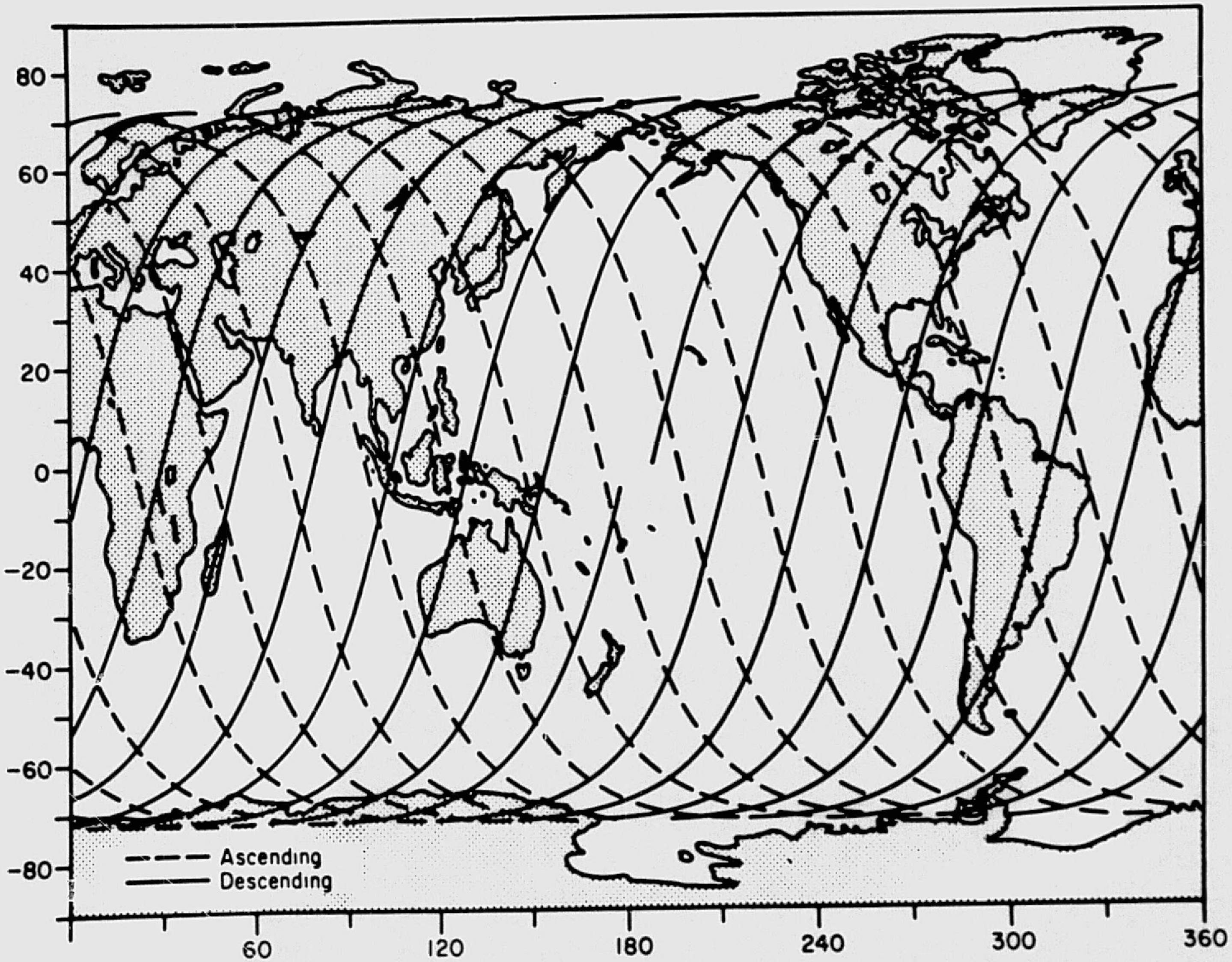


Figure 3.–SEASAT-A orbital ground track during one day.

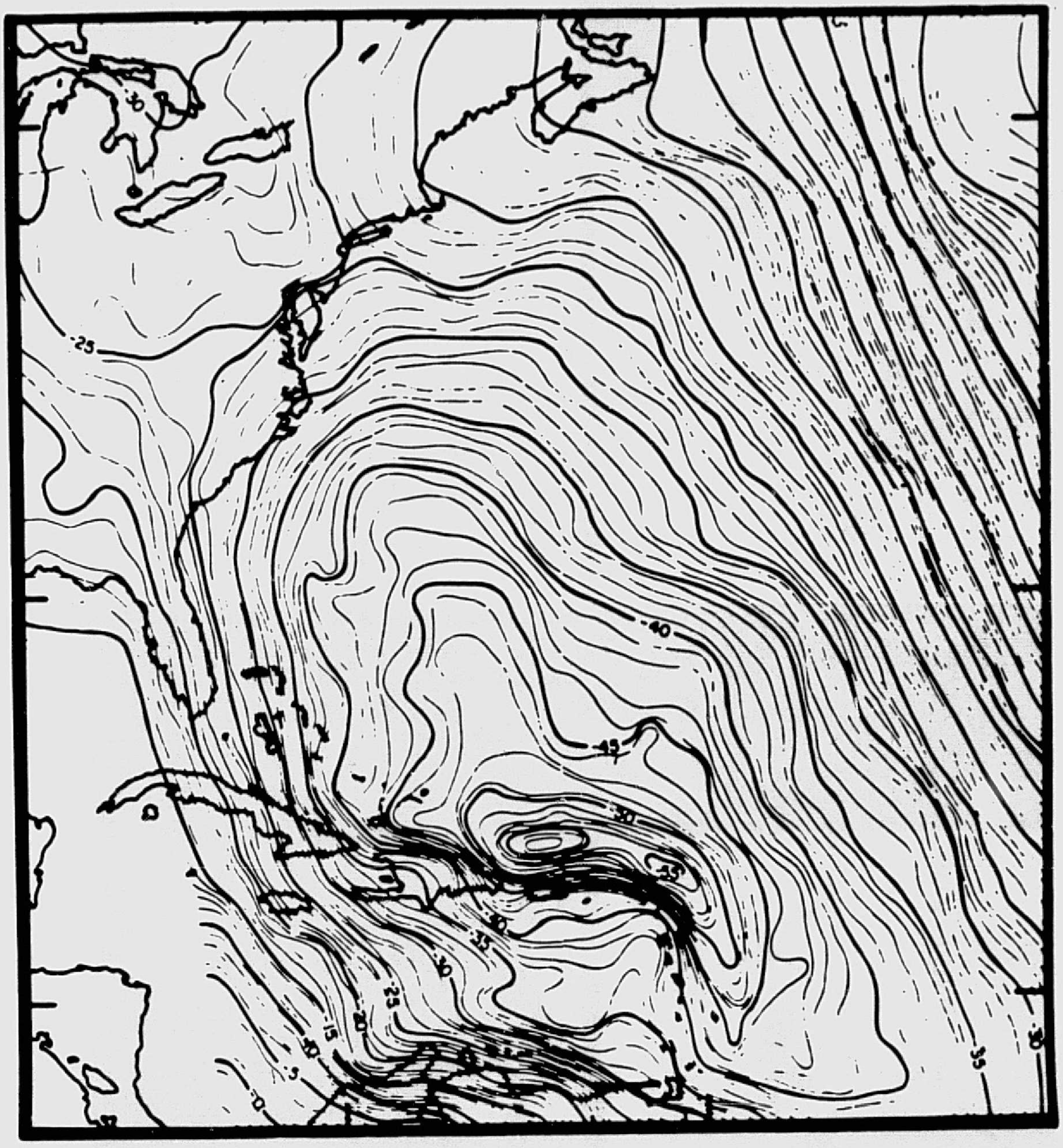


Figure 4.–Geoid in the Western Atlantic (elevations in meters).

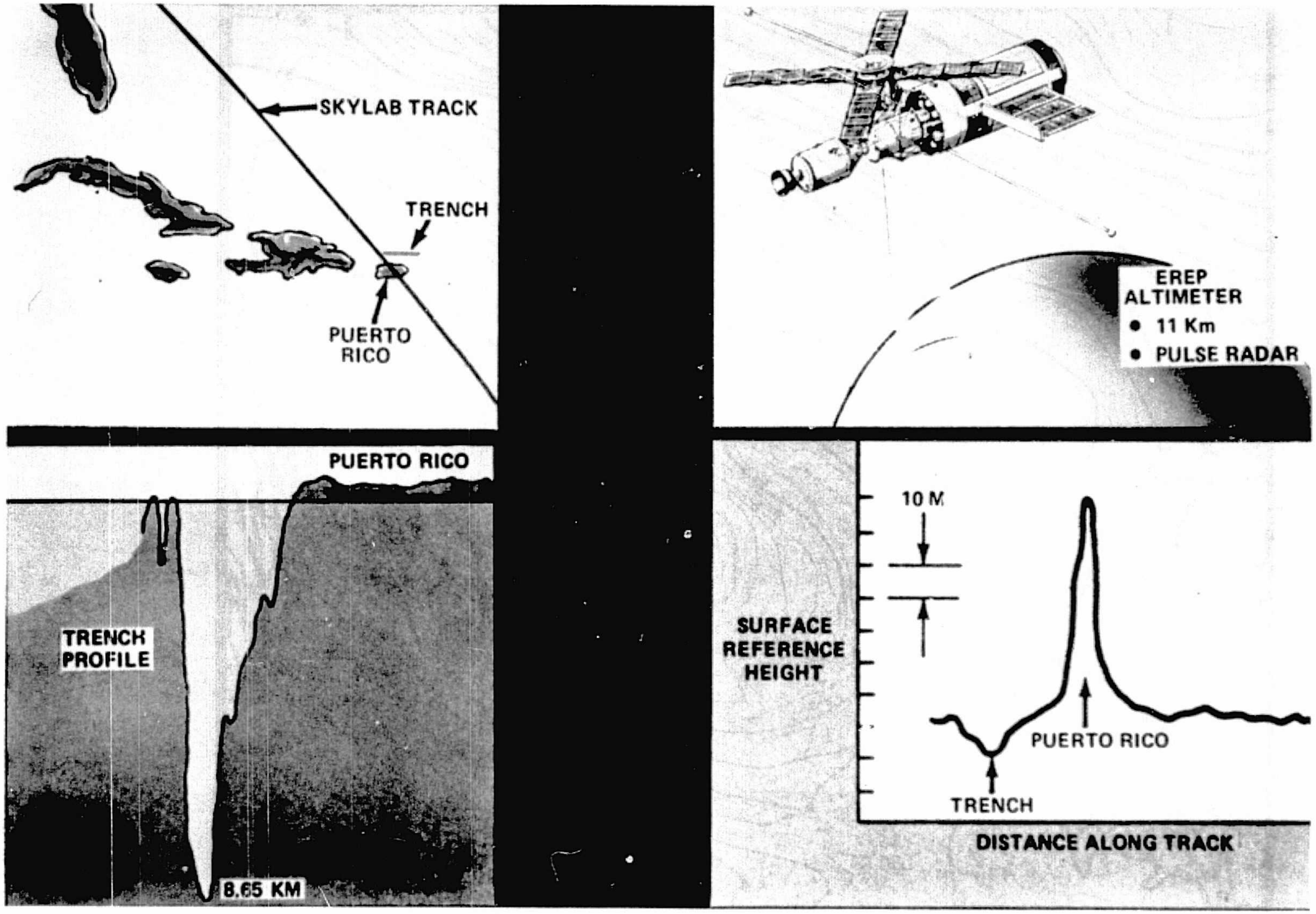


Figure 5.–Geoidal studies: Puerto Rico Trench.

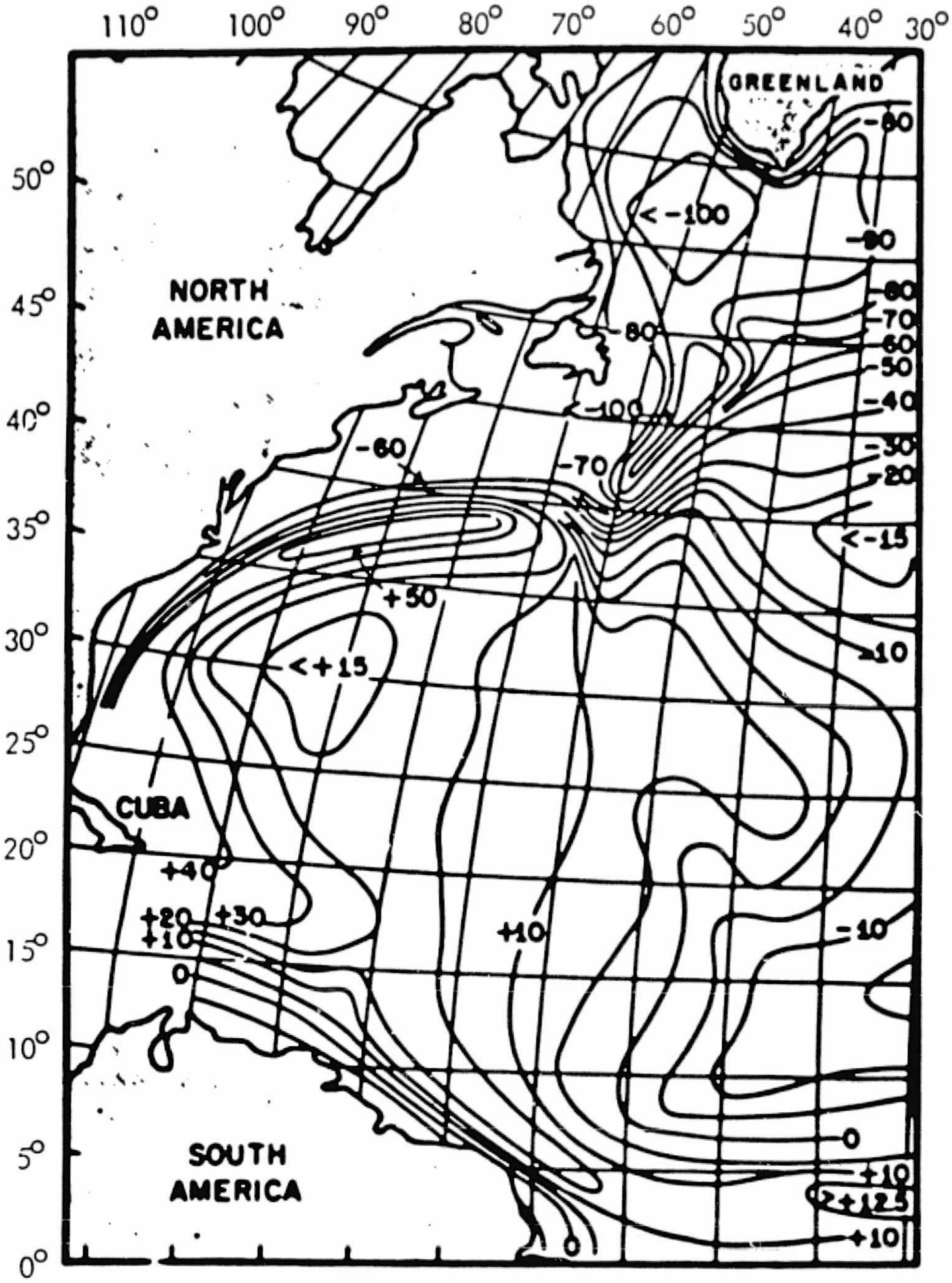


Figure 6.–Sea surface topography in the western Atlantic (elevation in centimeters).

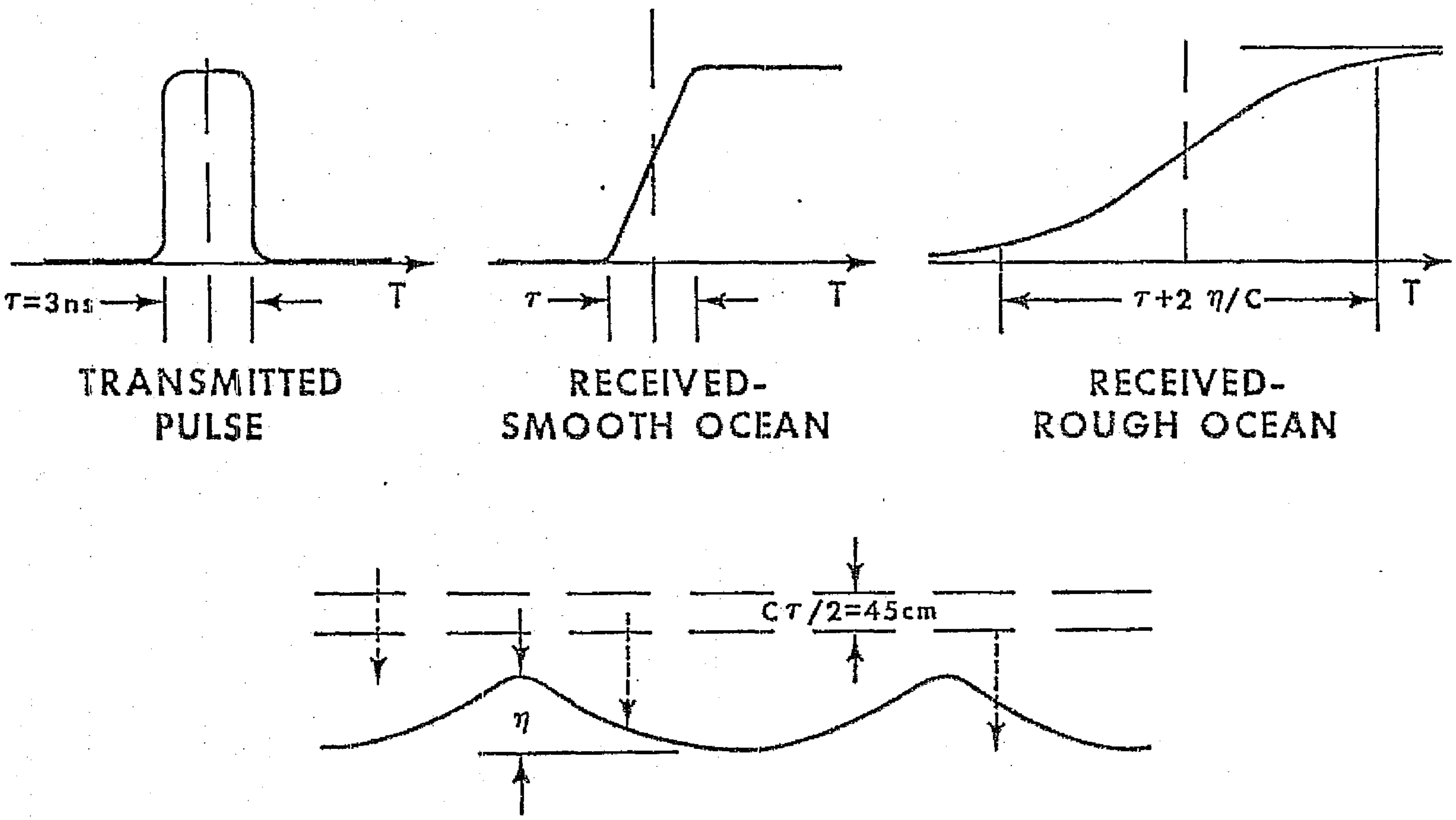


Figure 7.–Radar pulse broadening due to ocean waves.

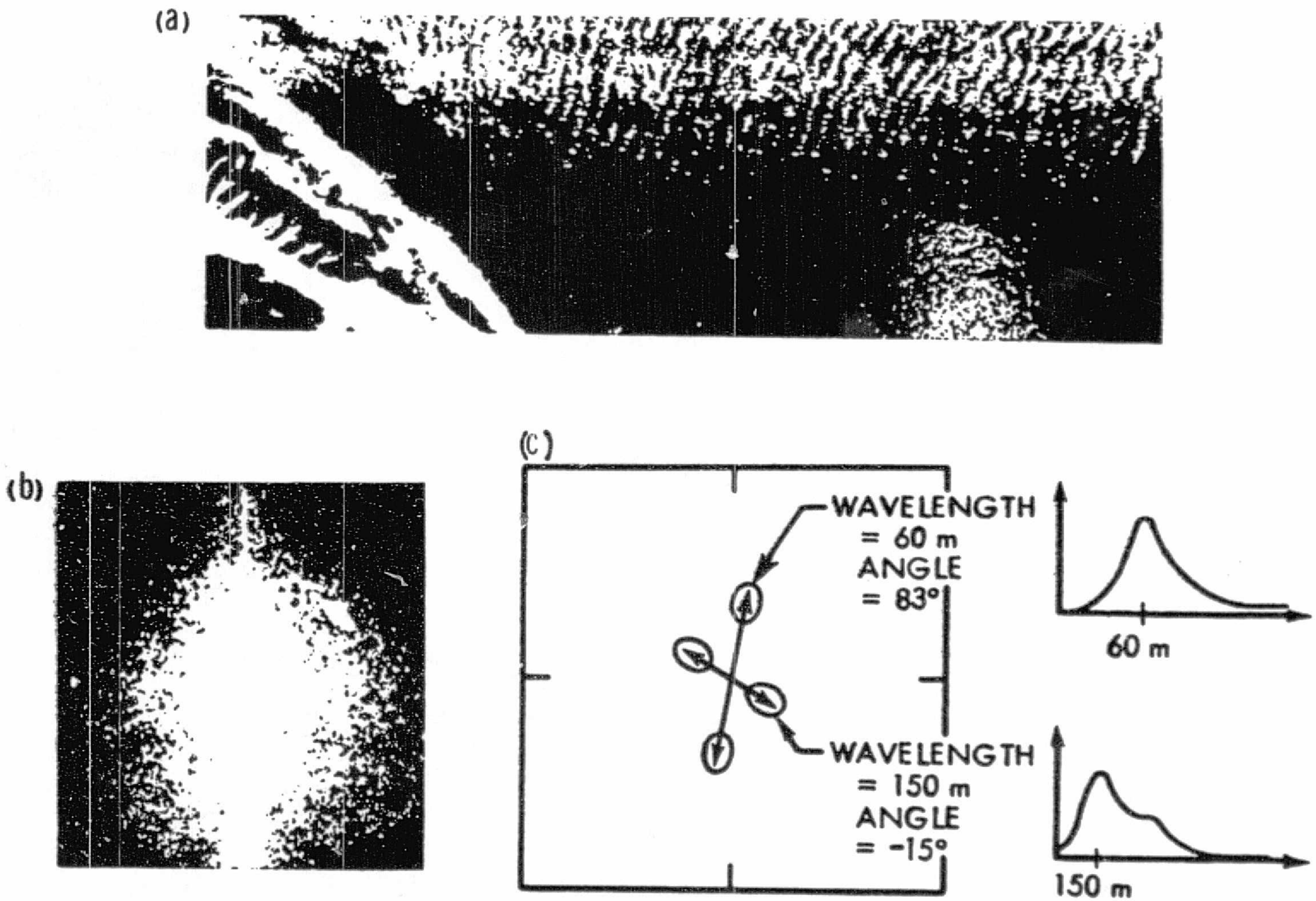


Figure 8.–Ocean wave image and wave spectrum from imaging radar. (a) Radar image of ocean waves; (b) Two dimensional fourier spectrum of figure (a); (c) Two wave patterns are clearly visible, the axes correspond to the frequency of the wave. The two right hand side curves correspond to the intensity of the spectrum along the two lines shown.

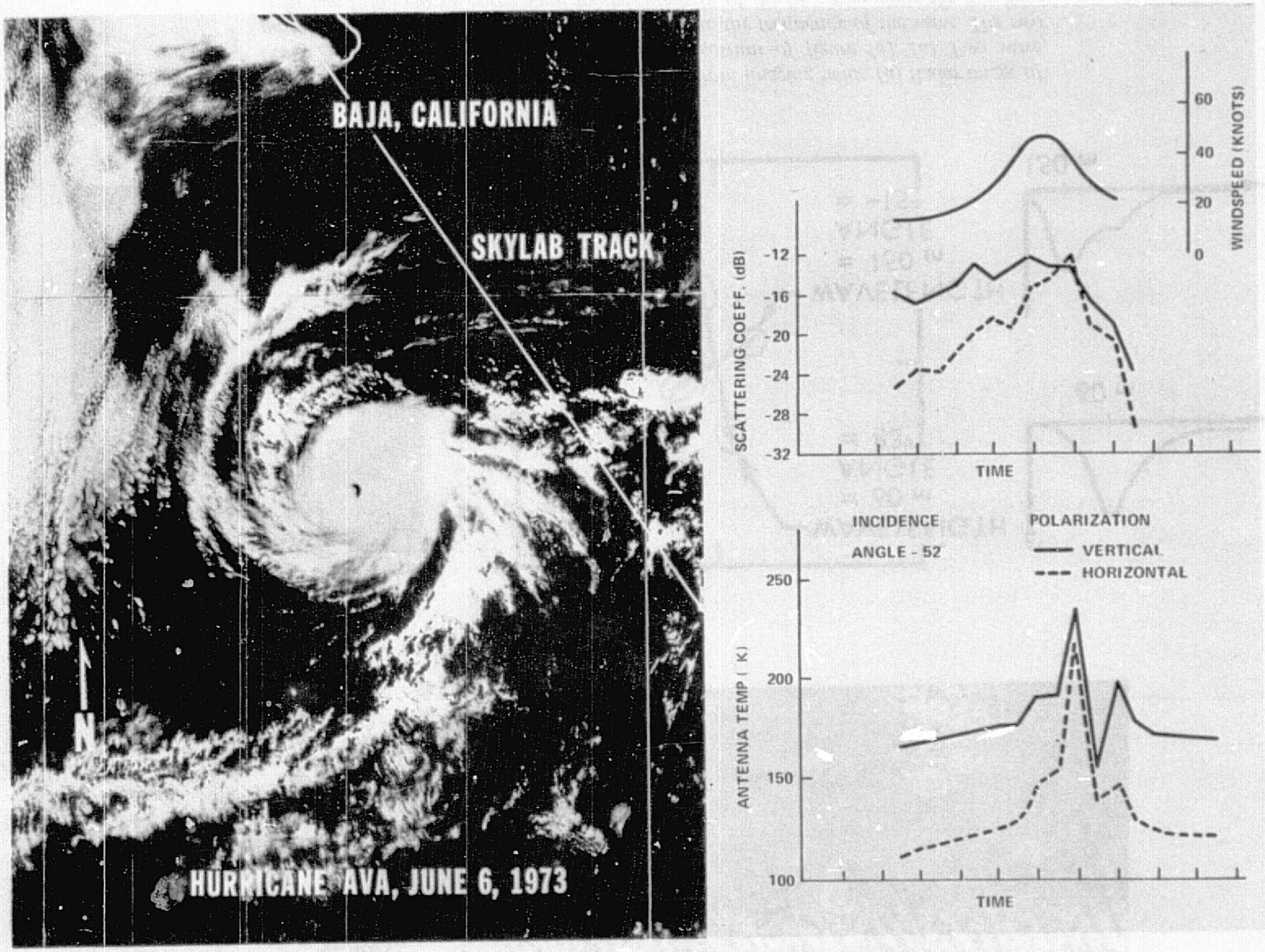


Figure 9.–Hurricane Ava observations (June 6, 1973).

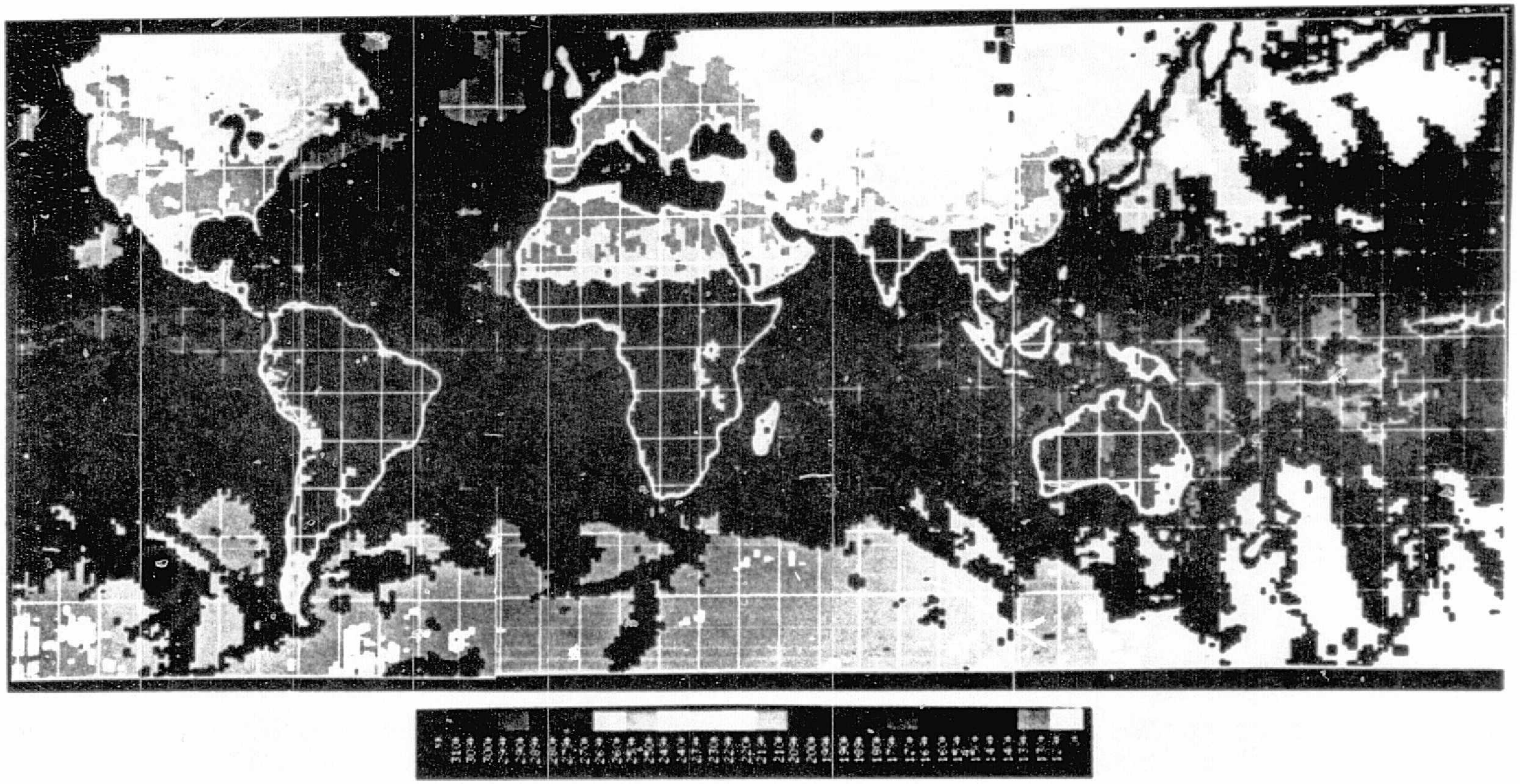


Figure 10.–Radio brightness of the world; Nimbus-5 electrically scanned microwave radiometer (λ = 1.55 cm). January 12-16, 1973.

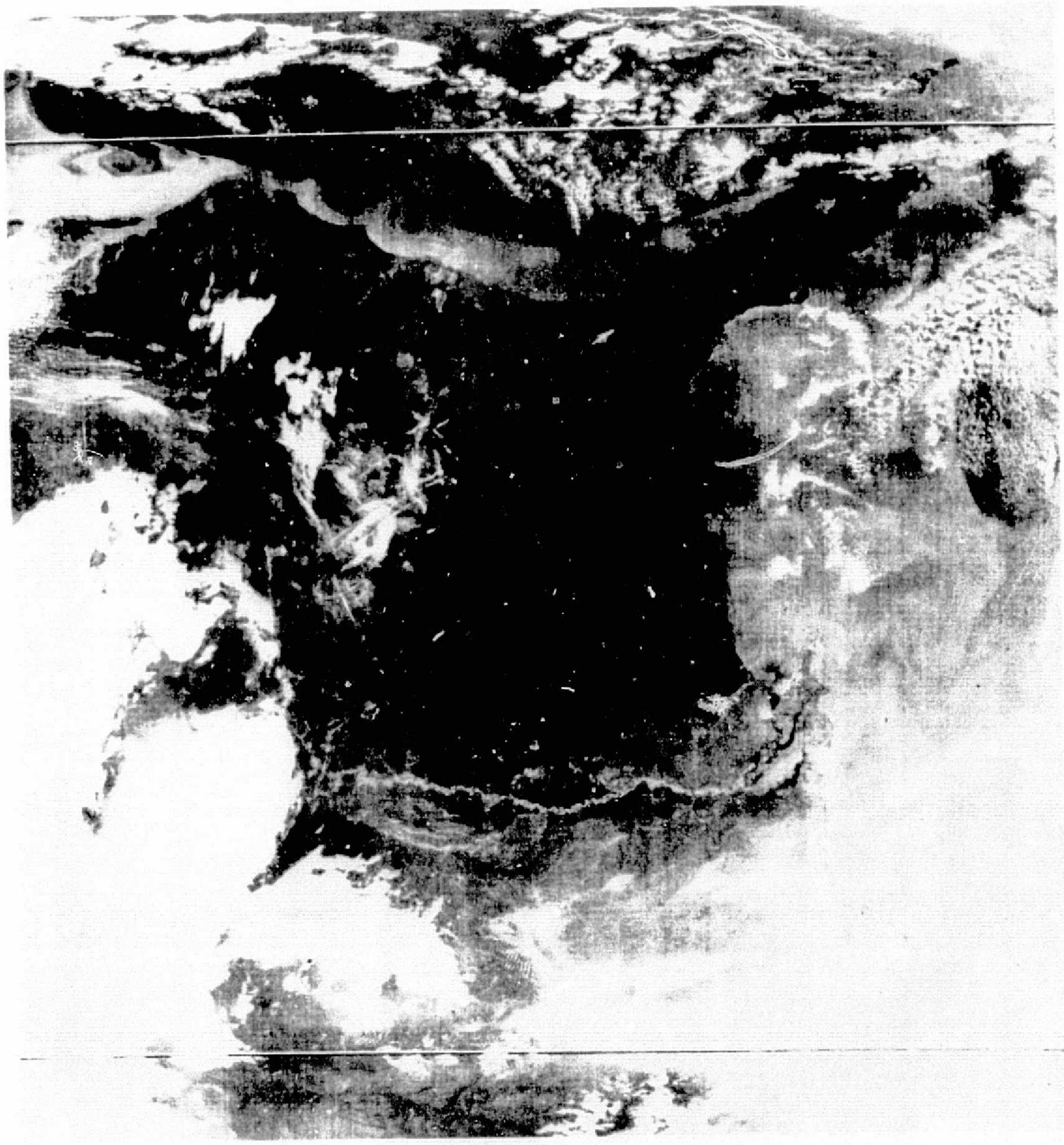


Figure 11.–Infrared radiometer image of the Southeast U.S.

C. 3

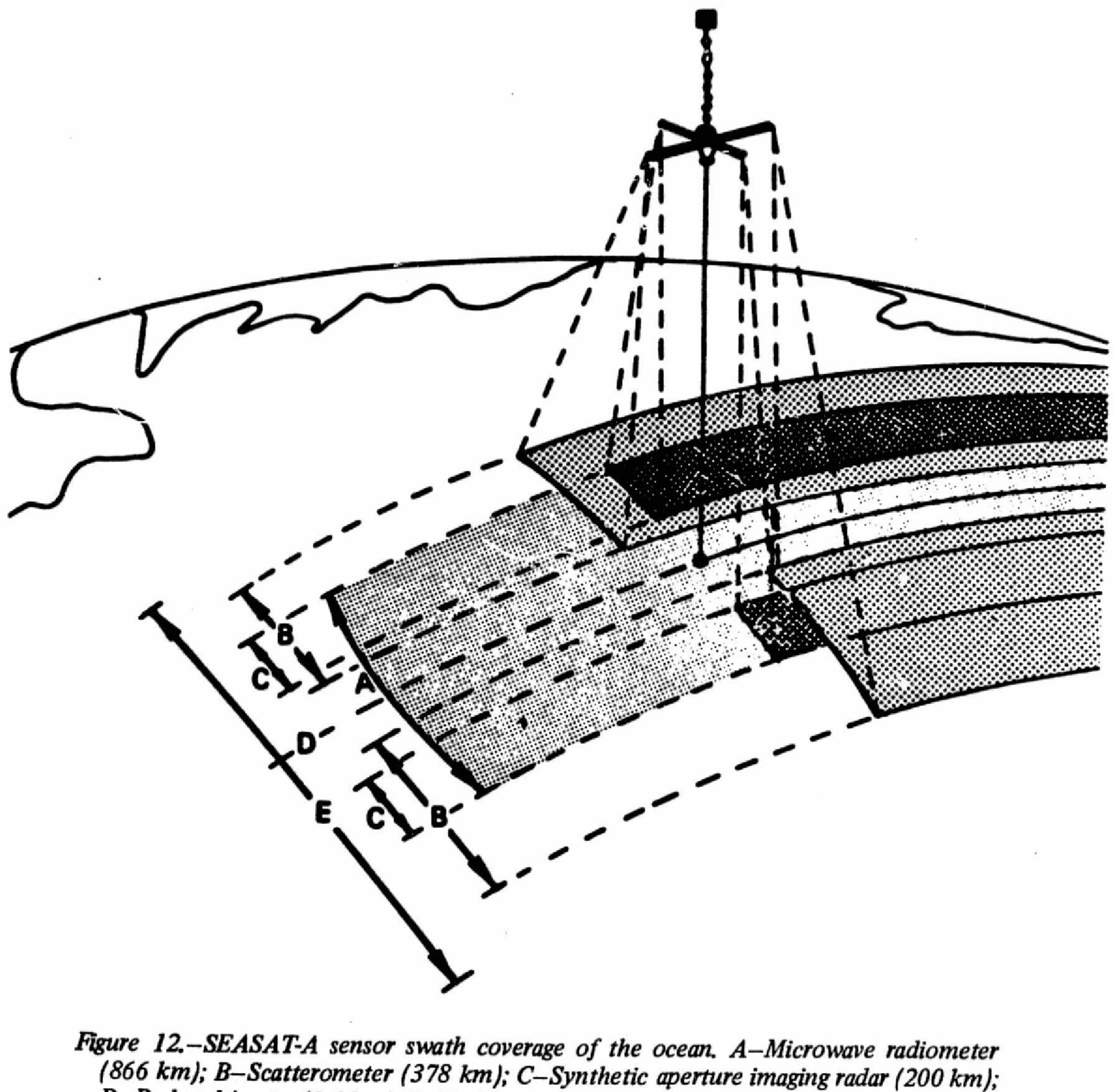


Figure 12.–SEASAT-A sensor swath coverage of the ocean. A–Microwave radiometer (866 km); B–Scatterometer (378 km); C–Synthetic aperture imaging radar (200 km); D–Radar altimeter (1.6 km); E– Visible and infrared imag. full track.

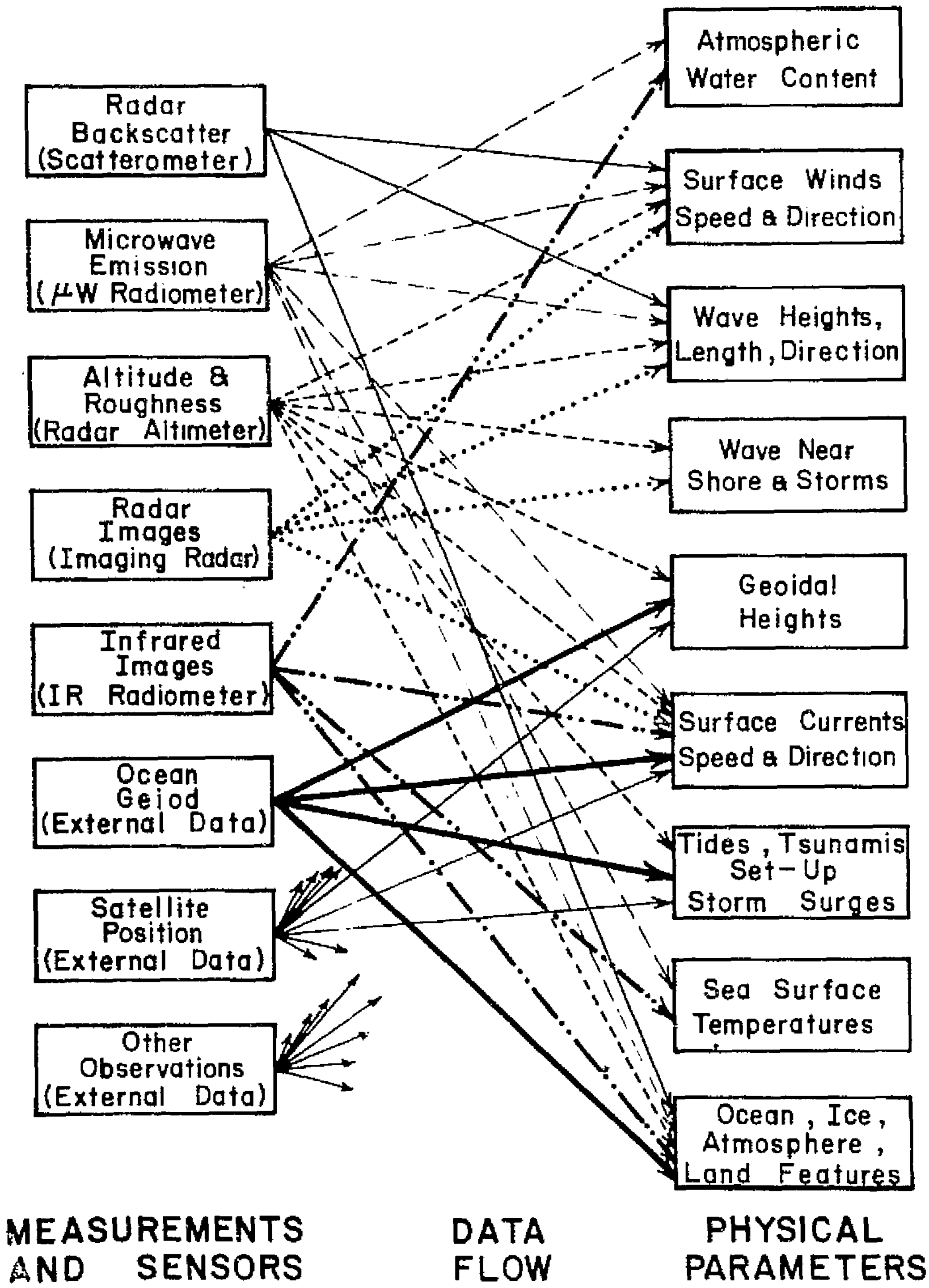


Figure 13.–Relationships between SEASAT-A instruments and physical parameters.

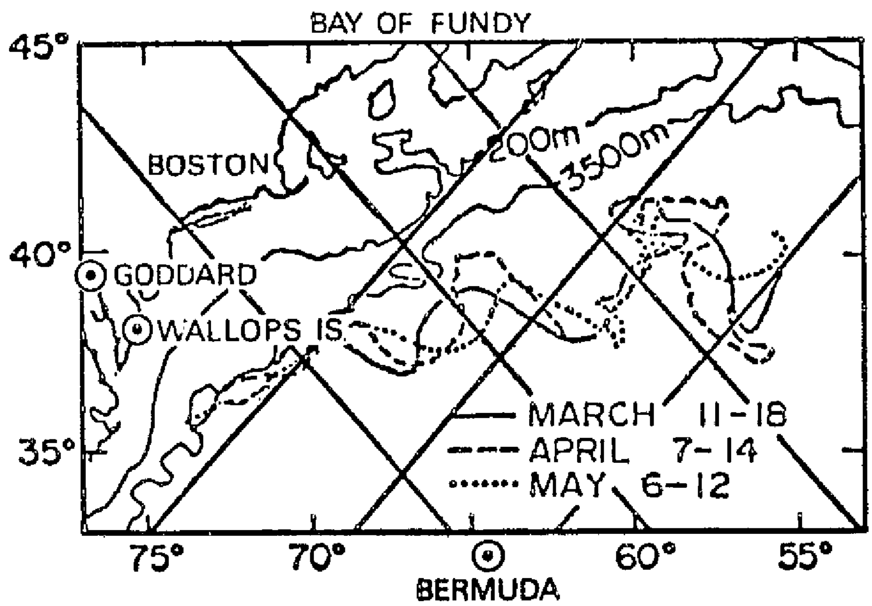


Figure 14.–Gulf Stream meanders and satellite altimeter sampling density.

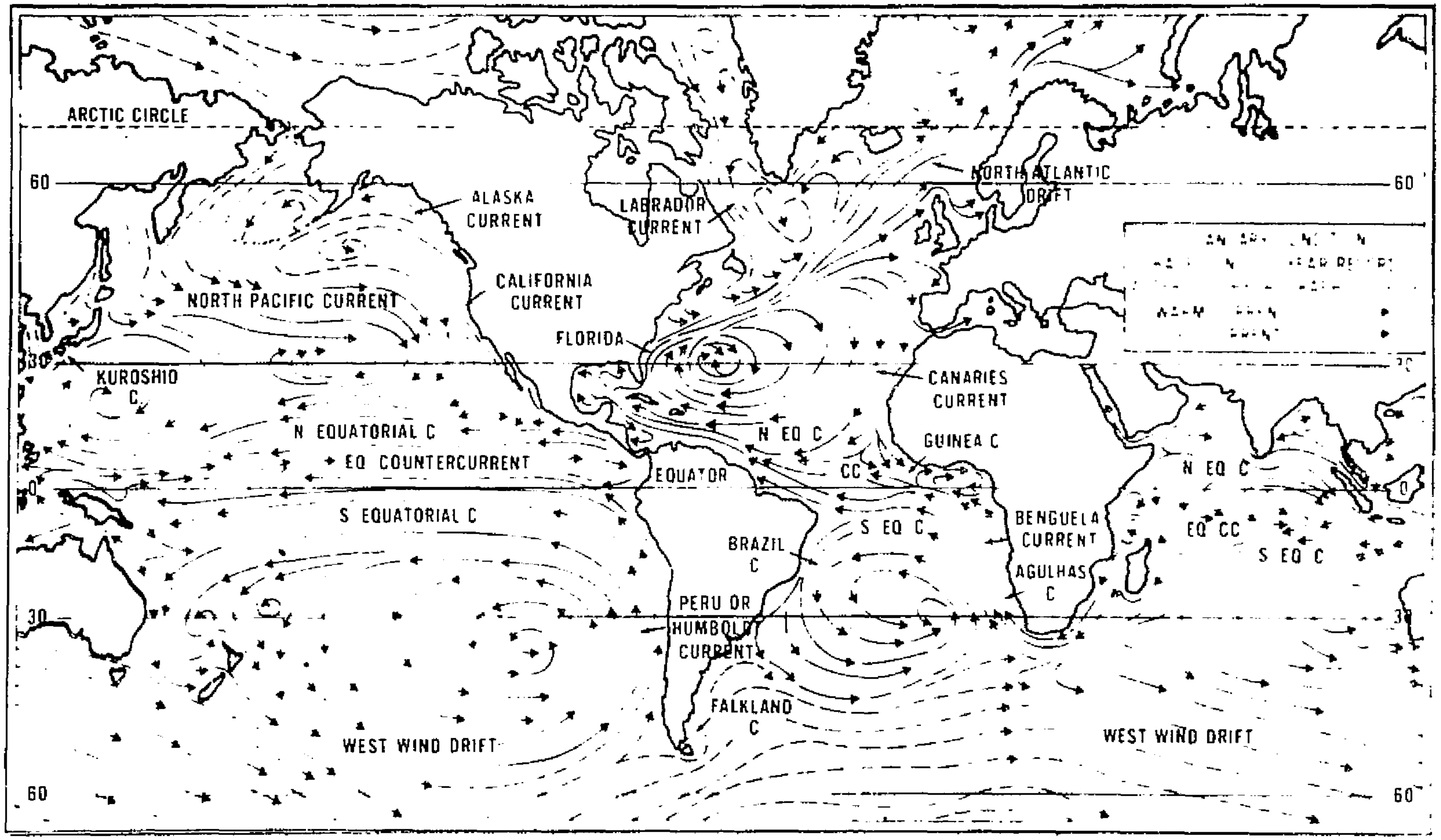


Figure 15.–World map of average surface drifts and currents of the oceans for the month of JANUARY. (Based upon data of the U.S. Navy, Oceanographic Office. From A. N. Strahler (1960), Physical Geography, New York, John Wiley & Sons.)